NPS-SE-11-002

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

ROVING UAV IED INTERDICTION SYSTEM

Capstone Design Project

by

MSSE Cohort 311-093A

Wayne Bechtel, Nathaniel Hathaway, Trevor Jerdee
Eric Laskey, Jill McConaghy, Lisa Quade
Kariym Smith, Scott Sparrow, James Tuey

March 2011

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

NAVAL POSTGRADUATE SCHOOL

Monterey, California 93943-5000

This report was prepared for the Chairman of the Systems Engineering Department in pursuit of the degree of Master of Science in Systems Engineering.

This report was prepared by:

Wayne Bechtel
Nathaniel Hathaway
Trevor Jerdee
Eric Laskey
Jill McConaghy
Lisa Quade
Kariym Smith
Scott Sparrow
James Tuey

Reviewed by:

Mark Rhoades
Capstone Co-adviser

Joseph W. Sweeney
Capstone Co-advisor

Clifford Whitcomb, Ph.D. CSEP
Department of Systems Engineering

Released by:

Karl A. van Bibber, Ph.D.
Vice President and Dean of Research

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01-03-2011	Technical Report	

4. TITLE AND SUBTITLE	
Roving UAV IED Interdiction System	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Wayne Bechtel, Nathaniel Hathaway, Trevor Jerdee Eric Laskey, Jill McConaghy, Lisa Quade Kariym Smith, Scott Sparrow, James Tuey	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER** NPS-SE-11-002
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES
The views expressed in this report are those of the authors and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

14. ABSTRACT
In support of the Naval Postgraduate School's Systems Engineering Capstone, a project team was formed from Cohort 311-093A to perform an analysis on the possibility of utilizing Unmanned Air Vehicles (UAVs) in campaign against improvised explosive devices (IEDs). The goal of the project was to determine if a weapon system is feasible to increase capabilities to the warfighter in the fight against the IED threat. The project scope was limited to the UAV classes with local (squad/battalion) control to provide an organic increase in capabilities; specifically Tier I (man-portable) and Tier II (tactical) families of UAVs. Modeling and simulation, warhead analysis, and a cost analysis were used to score the proposed alternatives on specific Key Performance Parameters. This information was analyzed and a recommendation was made to only arm the Tier II UAV using a small missile.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: Unclassified			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified	UU	295	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF EQUATIONS

ACRONYMS

AD	Anderson-Darling
AGL	Above Ground Level
AK	Avtomat Kalashnikova
AO	Area of Operations
AoA	Analysis of Alternatives
BDA	Battle Damage Assessment
BOC	Bombing on Coordinate
C	Apparent Contrast
C2	Command and Control
CAIV	Cost as an Independent Variable
CBRN	Chemical, Biological, Radiological, Nuclear
CCD	Charge-Coupled Device
CCIP	Continuously Computed Impact Point
CCRP	Continuously Computed Release Point
CEA	Captured Enemy Ammunition
CEP	Circular Error Probable
C-IED	Counter- Improvised Explosive Device
CLU	Command-Launch Unit
COA	Certificate of Authorization
CONOPS	Concept of Operations
COP	Common Operational Picture
CTC	Combat Training Center
dB	Decibels
DEP	Deflection Error Probable
DMPI	Desired Mean Point of Impact
DPG	Defense Planning Guide
EFP	Explosively Formed Penetrator
EO	Electro-Optical

EOD	Explosive Ordinance Disposal
EW	Electronic Warfare
F2T2EA	Find, Fix, Track, Target, Engage, Assess
FAA	Federal Aviation Administration
FCC	Fire Control Computer
FFBD	Functional Flow Block Diagram
FOB	Forward Operating Base
FOV	Field of View
FPS	Frames Per Second
	Feet Per Second
FSU	Former Soviet Union
GCS	Ground Control Station
GPS	Global positioning system
HALE	High Altitude Long Endurance
HOQ	House of Quality
IAI	Israeli Aerospace Industries
IDEF0	Integration Definition: Functional Model
IED	Improvised Explosive Device
INS	Inertial navigation system
InSb	Indium Antimonide
IR	Infrared
ISR	Intelligence, Surveillance, and Reconnaissance
	Israel
ISTAR	Intelligence, Surveillance, Target Acquisition, and Reconnaissance
IW	Irregular Warfare
J	Joules
JCREW	Joint Counter Radio-Controlled Electronic Warfare
JDAM	Joint Direct Attack Munition
JIEDDO	Joint IED Defeat Organization
JIMM	Joint Integration Mission Model

JUAS	Joint Unmanned Air System
KPP	Key Performance Parameters
LAR	Launch Acceptable Region
Lb_F	Force Pounds
LOBL	Lock On Before Launch
LOS	Line Of Sight
LTA	Lighter-Than-Air
MALE	Medium Altitude Long Endurance
MANPADS	Man-Portable Air Defense System
METL	Mission Essential Task List
MOE	Measure of Effectiveness
MOP	Measures of Performance
MPI	Mean point of impact
MTBF	Mean Time Between Failure
MTOW	Maximum Take-Off Weight
MTTR	Mean Time to Repair
NATO	North Atlantic Treaty Organization
NCCA	Naval Center for Cost Analysis
NGTS	Next Generation Threat System
NM	Nautical Miles
NPS	Naval Postgraduate School
NPV	Net Present Value
OEF	Operation Enduring Freedom
OMB	Office of Management and Budget
OMOE	Overall Measure of Effectiveness
PAWS	Precision Attack Weapon System
PCI	Pre-combat Inspections
PIR	Passive Infrared
	Priority Information Requirements
P_{HIT}	Probability of Being Hit

P_K	Probability of Kill
$P_{K\|HIT}$	Probability of Kill if Hit
P_L	Probability of Weapon Launch
P_s	Probability of Mission Success
Psi	Pounds per Square Inch
QFD	Quality Function Deployment
REP	Range Error Probable
RF	Radio Frequency
RFI	Request For Information
ROE	Rules of Engagement
RPG	(US) Rocket-powered grenade
	(CIS) Raketniy Protivotankoviy Granatomet
RSP	Render Safe Procedures
RSTA	Reconnaissance, Surveillance, Target Acquisition
RUINS	Roving UAV IED Interdiction System
S&A	See and Avoid
SAL	Semi-Active Laser
SE	Systems Engineering
SME	Subject Matter Expert
SSPD	Single Sortie Probability of Damage
SU	Situational Understanding
TOF	Time of Flight
TPM	Technical Performance Parameter(s)
TPO	Technical Program Office
TTP	Tactics, Techniques, and Procedures
TV	Television
UAS	Unmanned Aircraft System
UAV	Unmanned Air Vehicle
U.S.	United States
VBIED	Vehicle Borne Improvised Explosive Device

VOSS	Vehicle Operated Sensor System
VTOL	Vertical Take-Off and Landing
WMS	Weapons Management System

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

This report presents a feasibility study for weaponizing small Unmanned Air Vehicles (UAVs) for campaigns against Improvised Explosive Devices (IEDs). Counter-IED (C-IED) solutions depend not only on advanced technology, but also on a combination of superior tactics and timely intelligence. The primary goal of the C-IED mission is to assist in force protection through the implementation of persistent surveillance, dependable detection, and the ability to make swift and decisive responses in any engagement situation.

The project was loosely based on an Army Request for Information (RFI), which requested arming of the Shadow 200 class of Unmanned Air Vehicle (UAV). The project scope was limited to the UAV classes with local (squad/battalion) control to provide an organic increase in capabilities, specifically Tier I (man-portable) and Tier II (tactical) families of UAVs. To further scope the project, integration of weapons was to require no major changes to the UAV itself or its current Intelligence, Surveillance, and Reconnaissance (ISR) mission.

A systems engineering approach was developed and utilized to determine the feasibility of weaponizing the smaller UAV. The Systems Engineering process used is detailed further in the report and consists of the following major phases: problem definition, identification of existing capabilities, alternative design research, modeling and simulation of alternatives, analysis of alternatives, and recommendation of a solution. Current military interest in the UAV and C-IED missions lead the team to find stakeholders to help shape the requirements of the project. Three primary stakeholders were identified. They include the C-IED Technical Program Office (TPO), the Precision Attack Weapon System (PAWS) TPO, and the Irregular Warfare (IW) TPO. Discussions with the stakeholders shaped the problem statement and provided feedback to questionnaires designed to rank the importance of Measures of Effectiveness (MOE) and Measures of Performance (MOP).

Several research topics are discussed in the paper as they pertain to the detectability of both the UAV by IED emplacement teams and detectability of the IED teams by the UAV optics. The team then researched currently available weapons, both lethal and non-lethal, for possible use in the solution. Before transitioning into modeling and simulation, the possible weapons were down-selected based on requirements and the outcome was eight alternatives.

Modeling and Simulation was used to explore the performance of the proposed alternatives. Both the weapons effects, as dispensed by the UAV and at impact, were modeled. From this effort, two clear candidate weapons were selected. From the data collected during simulation, only the SAL/GPS guided bomb (GB-1) or a small guided missile (M-4) should be the primary weapons systems considered. A warhead kill analysis was done and it was found that all weapons dispensed from the Tier II surrogate UAS caused minimal damage to collateral targets on the outer targeting zone.

An aerodynamics analysis of a Tier II UAV with the candidate weapons was conducted. It was found that adding a weapon system to a Tier I and Tier II UAV has a significant impact on the aerodynamic performance of the baseline system. Due to physical limitations of the Tier I UAV, it was not considered a feasible platform and the analysis moved forward with Tier II UAV only. The RUINS team recommends that any weapon system selected for use on a small UAV should emphasize minimizing drag for both the weapon and the mounting hardware.

The cost analysis suggests that the small missile (M-4) weapons option offers the best “bang for the buck” in a cost benefits analysis. The M-4 weapon had the second highest Overall Measure of Effectiveness (OMOE) and second lowest Net Present Value (NPV). Although the micro UAV (M-5) weapon option had the highest OMOE, it was ruled out because of its high cost. The basic Bomb weapon had the lowest NPV, but it was ruled out due to its low OMOE score.

The recommended weapon for arming the Tier II UAV was the small guided missile (M-4), demonstrating high accuracy, maximizing UAV stand-off range, and demonstrating cost effectiveness while minimizing the impacts on the baseline UAV.

I. INTRODUCTION

Since the beginning of the Global War on Terrorism, Improvised Explosive Devices (IEDs) have developed into one of the most deadly threats to both Coalition forces and civilians across Iraq and Afghanistan. Although the technologies and materials utilized in IEDs are often quite simple, Counter-IED (C-IED) solutions have proven to be extremely difficult to identify and implement. Successful C-IED depends not only on advanced technology, but also on a combination of superior tactics and timely intelligence. The primary goal of the C-IED mission is to assist in force protection through the implementation of persistent surveillance, dependable detection, and the ability to make swift and decisive responses in any engagement situation.

In an effort to adequately address the rapidly evolving IED threat, C-IED technologies and tactics are in constant development. Multiple theaters of operation present diverse battlefield conditions, demanding a diligent effort to improve current C-IED technology. In the words of the Counter Explosive Hazards Center Director, Lieutenant Colonel Eric Goser, "It's kind of an unrelenting game of catch-up." Given the challenges of the C-IED mission, Goser said, "The frustration is ... how do I get out in front of him [the enemy]? The reward is when you do get ahead of them for that minimal amount of time (O'Connor 2010)." Ensuring the best tools and technologies are available to Coalition forces allows development of the most effective C-IED solutions. The future of C-IED lies with Unmanned Air Vehicles (UAV) in Unmanned Aircraft Systems (UAS) to offer capabilities that aid in the battle against the IED threat.

Unmanned aircraft are currently being used to aid in the C-IED mission. A UAV can be used to monitor suspected bomb-makers to predict their activities through increased surveillance. Once an IED emplacement team has been located by a UAV, Coalition forces can avoid or persecute the insurgents. This research document intends to show that providing an armed UAV down at the squad level may give Coalition forces the extra tool needed to prevent or neutralize an IED attack.

A. Background

The conflicts in Iraq and Afghanistan have been largely asymmetric. The overwhelming military force employed by Coalition forces has caused the adversaries to employ guerilla tactics instead of traditional military confrontations. The most effective weapon, particularly in Iraq, has been the IED. The IED is a form of anti-personnel or anti-vehicular mine built from scavenged parts and explosive devices (Wilson 2006). Based on recent disturbing news reports, the IED has rapidly become the weapon of choice in Operation Enduring Freedom (OEF).

1. The IED Threat

The IED's low cost and ease of construction have made it the preferred weapon of entities with no conventional military. Although IEDs have been used for hundreds of years, there has been a significant expansion in the use and effectiveness of IEDs in the twentieth century due to increased availability of both military and dual-use explosives.

Variations of the physical architecture are nearly endless due to the ad-hoc nature of an IED. IEDs include the following common components: a main charge, an initiating system, and a casing. Examples of these components are presented in Figure 1.

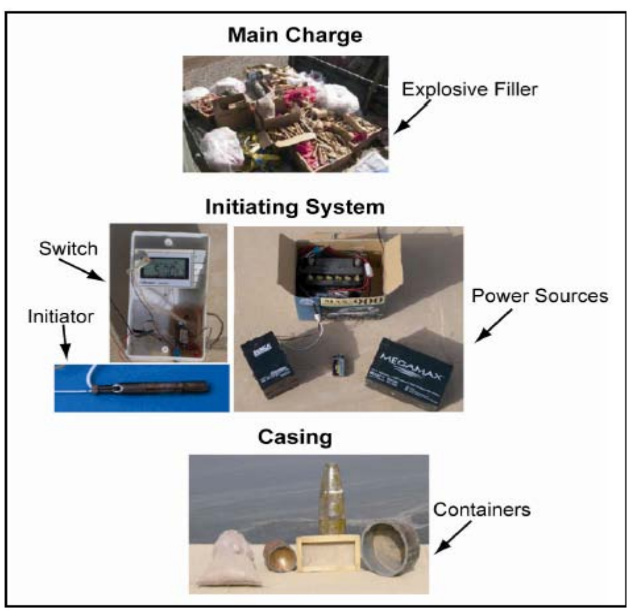


Figure 1 - Example IED Common Components after (U.S. Army 2008)

In Iraq, the most commonly used explosive charges were salvaged artillery shells due to their availability, ease of use, and inherent fragmentation capabilities (USMC 2005). Conversely, 80 percent of IEDs in Afghanistan are constructed using homemade explosives developed from ammonium nitrate, a typical farm fertilizer (JIEDDO 2010). Propane tanks and fuel cans have been added to some IEDs to further increase the blast. Chemicals, such as battery acid, have been found surrounding the charge, and in some instances, nails, ball bearings, and other similar hardware have been used to increase the potential for damage and injury to the forces.

The uses of IED fall into five general categories: Static, Disguised Static, Disguised Moveable, Thrown/Projected, and Hoax. The Static category contains IEDs that have no concealment measures: once the IED is placed it is not intended to be moved. The Disguised Static category contains IEDs that can be buried or camouflaged using appropriate materials and placed at or near a target. Disguised moveable are camouflaged IEDs, which are designed to be moved. Vehicle Borne IEDs (VBIED) and suicide bomber vests are some common means of moving the device once it has been constructed and armed. Thrown or Projected IEDs are used in a manner similar to grenades and are typically thrown off overpasses or bridges. Hoax IEDs are non-operational IEDs used for gathering intelligence. The enemy observes force reactions to the hoax to better develop future tactics (USMC 2005).

Data illustrating the trend of IED incidents associated with recent conflicts in Afghanistan are shown in Table 1. IED incidents, IEDs found, IED attacks, and Coalition forces killed or wounded in action by IEDs have all increased each year since 2007. The data in the table suggests IED threats have evolved to become a significant threat to United States (U.S.) and Coalition Forces. Lieutenant General Michael Oates stated “In future wars, IEDs will be more sophisticated and the technologies of these devices will become more difficult to defeat” (JIEDDO 2010).

Table 1 - Afghanistan Trend Chart June 2010 (JIEDDO 2010)

Incident	Totals			
	CY07	CY08	CY09	CY10 (As Of June)
IED Incidents	2,677	3,867	8,206	5,921
IEDs Turned In	177	118	237	150
Found/Cleared	1,158	1,892	4,226	3,200
Ineffective IED Attacks	1,136	1,470	2,923	1,923
Effective Attacks	206	387	820	648
Coalition Forces Killed in Action	77	183	322	182
Coalition Forces Wounded in Action	415	790	1,813	1,303

Continuing development of technology and tactics must continue to protect both the troops and innocent civilian population from this insidious threat. UAVs may provide a fast, flexible platform for extending C-IED capabilities.

2. Unmanned Air System Capabilities

The Coalition's primary UAS operational capabilities focus is intelligence, surveillance, and reconnaissance. In recent years, the missions of some of the larger systems have expanded to include carriage of armaments. Capabilities and missions continue to evolve and develop as new needs arise. The C-IED mission presents one of the emerging areas for improved and expanded UAS capabilities.

In adapting UAS to be better suited for the C-IED mission, each of the elements contained in the UAS must be considered. As shown in Figure 2, the UAV is but a portion of the integrated UAS system. The UAV must provide the range, loiter time, airspeed, and altitude required by the mission. The mission packages must provide sensors and weapons with sufficient capabilities to detect, locate, and defeat IED threats. The human element must be adequately trained to respond with the appropriate tactics and force upon IED detection. The control element must enable commands to be processed quickly enough to meet response timelines for IED threats. The displays must provide operators with sufficient detail and accuracy to unambiguously determine the appropriate course of action against a detected IED threat. The communications architecture must allow data to be transmitted and received in real-time and not conflict with in-theatre air space

operations. Operational availability, reliability and supportability are critical to ensuring the overall effectiveness of UAS in C-IED applications.

Figure 2 - UAS Element Integration from (U.S. Army UAS Center of Excellence 2010)

There are many different sizes of fixed-wing UAVs currently in service. The Federal Aviation Administration (FAA) has divided UAS into categories based on several factors as follows (DoD 2009):

> *UAS (Cat I). Analogous to RC models as covered in AC 91-57. Operators must provide evidence of airworthiness and operator qualification. Small UAS are generally limited to visual line of sight (LOS) operations. Examples: Raven, Dragon Eye.*
>
> *UAS (Cat II). Nonstandard aircraft that perform special purpose operations. Operators must provide evidence of airworthiness and operator qualification. Cat II UAS may perform routine operations within a specific set of restrictions. Example: Shadow.*
>
> *UAS (Cat III). Capable of flying throughout all categories of airspace and conforms to Part 91 (i.e., all the things a regulated manned aircraft must do including the ability to see and avoid (S&A)). Airworthiness certification and operator qualification are required. UAS are generally built for beyond LOS operations. Examples: Global Hawk, Predator.*

The FAA made determinations concerning the airspace each type of UAS could use. These operational parameters were divided into the three categories as presented in Table 2.

Table 2 - FAA Restrictions on UAS Categories from (DoD 2009)

FAA Category	Regulations	Airspace Usage	Airspeed Limit, KIAS	Example Types unmanned, (manned)
RC Model Aircraft/UAS (Cat I)	None (AC 91-57)	Class G (< 1,200 ft AGL)	< 100 (proposed)	Dragon Eye, Raven (none)
Nonstandard Aircraft/UAS (Cat II)	14 CFR 91, 101, 103	Class E, G, & non-joint-use Class D	< 250 (proposed)	Shadow (Light-sport aircraft)
Certified Aircraft/ UAS (Cat III)	14 CFR 91	All	None	Predator, Global Hawk (Airliners)

The Joint Unmanned Air System (JUAS) Certificate of Authorization (COA) established a five-level categorization for UAS as presented in Table 3. These categories were accepted by all services on 25 November 2008. The Marines have defined the term "tiers" to refer to the various categories, while the Air Force, Army, and DoD use the term "groups." The tiers were determined by takeoff weight, operating altitude and speed.

Tiers I, II and III were targeted for consideration in the C-IED solution presented in this Capstone Project. Each tier has specific support requirements and operational restrictions. Tier I, containing the smallest of the UAV, may be transported by two men or less with specialized backpacks. UAVs in this tier are termed "man-portable." Tiers II and III are referred to as "tactical" UAS. The tactical UAS require more support equipment and personnel for their operations than man-portable. Tiers IV and V are "theater" UAS and were beyond the scope of this investigation. Both man-portable and tactical UAS may be controlled at the local level and offer an organic capability to local troops. In contrast, control of theater UAS shift from local operations to theater level, allowing better management of airspace and the electromagnetic spectrum.

Table 3 - Unmanned Air Systems Groups (DoD 2009)

<table>
<tr><th>UAS Category</th><th>Maximum Gross Takeoff Weight (lbs)</th><th>Normal Operational Altitude (ft)</th><th>Speed (KIAS)</th><th>Current/Future Representative UAS</th></tr>
<tr><td>Tier I</td><td>0-20</td><td><1,200 AGL</td><td>100 kts</td><td>Wasp III, FCS Tier I, TACMAV, RQ-14A/B, BUSTER, BATCAM, RQ-11B/C, FPASS, RQ16A, Pointer, Aqua Tern, Puma</td></tr>
<tr><td>Tier II</td><td>21-55</td><td><3,500 AGL</td><td rowspan="2"><250</td><td>Vehicle Craft Unmanned Aircraft Systems, ScanEagle, Silver Fox, Aerosonde</td></tr>
<tr><td>Tier III</td><td><1,320</td><td rowspan="2"><18,000 MSL</td><td>RQ-7B, RQ-15, STUAS, XPV-1, XPV-2</td></tr>
<tr><td>Tier IV</td><td rowspan="2">>1,320</td><td rowspan="2">Any Airspeed</td><td>MQ-5B, MQ-8B, MQ-1A/B/C, A-160</td></tr>
<tr><td>Tier V</td><td>>18,000 MSL</td><td>MQ-9A, RQ-4, RQ-4N, Global Observer, N-UCAS</td></tr>
</table>

Representative UAVs are presented in Table 4. Tactical UAVs are identified by the shading of the table. Lighter-than-air (LTA) and vertical take-off and landing (VTOL) UAS are not included this study. The primary tasks of the listed UAS are to perform reconnaissance and surveillance. To accomplish this type of mission, all the above UAS have UAVs minimally equipped with some form of visual surveillance equipment. The majority of the man-portable UAVs are equipped with either visual or infrared (IR) cameras due to their limited payload capacity. Most of the tactical group carry cameras for both spectral bands at all times and include gimbaled mountings for better image stabilization and target tracking.

Table 4 - Representative Tier I - III UAS Systems (DoD 2009)

Name	Maximum Payload (lb)	Ceiling (kft)	Radius (nm)	Endurance (hr)
TACMAV	0.1	11	1.5	0.5
Wasp III	0.25	0.5	3	0.75
RQ-11 Pathfinder (Raven)	0.7	15	5	1.5
RQ-11 Swift/Dragon Eye	1.0	10	2.5	1.0
Aqua/Terra Puma	2-4	10	6	2.5
Buster	3.0	10	6	4
Silver Fox	5.0	16	20	8
Aerosonde	12	20	1,000	30
Scan Eagle	13	16	60	15
XPV-1 Tern	25	10	40	2
XPV-2 Mako	30	10	40	8.5
RQ-7 Shadow	60	14	60	6

It is believed that none of the UAVs in the table currently carry offensive weapons. The uses and missions of UAS are only expected to expand in the coming years. Delivery of a warfighting capability is the focus of future developmental efforts and of this capstone.

B. Systems Engineering Process

The systems engineering (SE) process used for this project was a modification of a process model proposed by John M. Green, formerly of Raytheon, now with the Naval Postgraduate School (NPS), for modeling a ship as a weapon system (Green March 27-29, 2001). As shown in Figure 3, some stages of the SE process contained multiple tasks and parallel efforts to develop multiple prototypes (models) for use in evaluation of alternatives. The output of the process was a design recommendation based on analysis and tradeoff studies, rather than a completed physical system. The following sections detail each phase of the process.

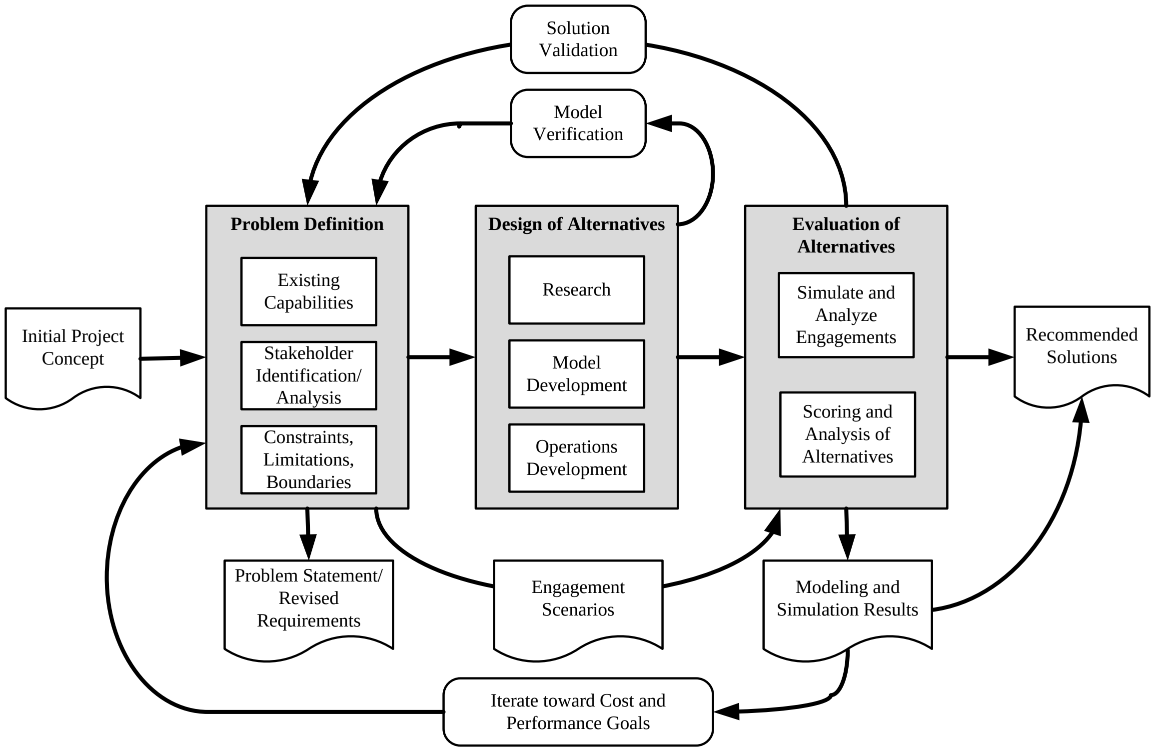


Figure 3 - Systems Engineering Process Model

1. Mission Requirements Determination Methodology

The project was proposed in response to a definite mission need: IED interdiction and prosecution. Additional refinement and fidelity of the mission requirements were developed after consultation with subject matter experts (SME) and stakeholders. Stakeholders were identified as representatives from the C-IED, Weapons, Irregular Warfare, and UAV communities. The required missions were thoroughly understood before a proper identification of the depth and scope of the true problem was ascertained. Design reference missions that closely represent operational missions were developed using information gathered from stakeholders. Using the developed reference missions, measure of effectiveness (MOE) metrics were identified for use in the analysis of alternatives and in validation of warfighter needs of the proposed solutions.

2. Problem Definition Phase

Following determination of accurate mission requirements, investigation and analysis were performed to aid in properly identifying and scoping the problem. Outputs

from the Problem Definition phase included a detailed problem statement, requirements to guide the later design and evaluation phases, and engagement scenarios for use in the evaluation phase.

a) Identification of Existing Capabilities

Research of existing capabilities was necessary to ensure that any proposed solution was not a duplicate of what is already available. Additionally, knowledge of existing capabilities allowed proposed solutions to augment the current solutions and ensure they do not detract from current solutions.

b) Stakeholder Identification and Analysis

Identification of parties that may have an input to the mission or solution was identified early in the SE process to ensure the problem was fully addressed from a variety of viewpoints. Each of the stakeholders had their own priorities including approach, boundaries, needs, and viewpoint. Performing a stakeholder analysis promotes an understanding of the different stakeholders, their relationship to the project, and their priorities. The stakeholders aided in the development of mission scenarios and identification of additional mission requirements. In addition, careful performance of stakeholder analysis aided in clearly delineating needs and wants. The stakeholders also acted as a verification authority for the selected MOEs and proposed additional metrics.

c) Identification of Constraints, Limitations, and Boundaries

The C-IED problem and proposed problem solution have a clearly identified boundary. Every possible nuance of the mission cannot be addressed within the constraints of the project. Other constraints or limitations preclude certain solutions for various political and logistical reasons. Identification of any limiting factors was done early in the problem identification process to help scope the tasks to be accomplished in the follow-on processes.

3. Design of Alternatives Phase

Information developed during the Problem Definition phase was used in combination with research, model development, and development of concept of operations to define possible means of satisfying the mission requirements. Models developed during this phase were verified against the requirements and expectations provided by the

Problem Definition phase. Measures of Performance (MOP) and Key Performance Parameters (KPP) were developed and verified during this phase. The developed requirements and metrics were utilized in the following Analysis of Alternatives (AoA) phase.

a) Alternative Design Research

Investigation of currently available technologies, implementations, and tactics was performed to identify possible components and approaches to a system solution. Research was conducted using academic and workplace library resources, internet resources, and interviews in an effort to determine the limits of what is technologically and logistically feasible within the timeframe of the project.

b) Model Development of Alternative Design Components

Design of system solutions for this project was accomplished by development of models as no physical system was delivered. The models developed were verified against input parameters as well as information developed and gathered during the Research phase to adequately model the components necessary for final system evaluation.

c) Model Verification

The models developed during this stage were analyzed against requirements and capabilities developed during problem definition to ensure that they accurately reflected the anticipated performance parameters. This iterative process was repeated until the models achieved an adequate level of accuracy required for the study.

4. Operations Development of Alternative Designs

A critical component to the system design was how to operate the system and its planned implementation. Development of operational methods and tactics were accomplished to provide a complete system solution for the AoA phase.

5. Analysis of Alternatives Phase

The mission scenarios developed during the Program Definition phase were used in concert with the verified models developed during the Design of Alternatives phase to evaluate the performance of the proposed solution systems, in a simulation environment, to determine the optimum weapon solution. The approach was iterative, as multiple solutions were expected to be developed. Results of modeling were used to evaluate

combined system performance against the metrics and other factors determined during Problem Definition and Design of Alternatives. The evaluation was performed in an effort to determine the solution that best meets cost and performance requirements and to develop data for validation of proposed system performance. Information developed during this phase was used for the generation of a final recommendation report. Simulating and scoring the alternatives for performance are the two major activities that were accomplished during this phase.

a) Simulate and Analyze Engagements of Proposed Alternatives

Mission simulations using the models developed during the previous phase and the scenarios developed during the Problem Definition phase were used to develop parameters and evaluation methods for comparison of proposed solutions. Many iterations of mission simulations included the full range of operational and system possibilities. Each mission simulation was analyzed to ensure accuracy remained comparable to others, allowing direct comparison of results.

b) Scoring and Analysis of Proposed Alternatives Performance

Selected metrics and methods were used to compare, contrast, and evaluate the performance of the various alternatives against each other in an effort to determine the optimum solution. The analysis included measures of cost as well as performance in the evaluations.

c) Solution Validation

Each possible UAV-weapon pairing simulated was evaluated against the requirements and documented stakeholder preferences to insure that the solutions would meet the operational needs. The observed solutions performances were compared with the measures of effectiveness to further aid the selection of the optimum solution.

6. Recommended Solution Development and Documentation

The successful completion of the previous phases provided information included in a final compiled evaluation and recommendation. This document contains a thorough discussion of the compete process coupled with a detailed analysis and reasoning behind the final recommended solution.

C. Scope

Several assumptions, limitations, and constraints were identified and in place for the duration of the project. Additional limitations on scope were expected to develop as a result of stakeholder interactions during the development process. The next sections detail the assumptions and the limitations and constraints identified for this project.

1. Assumptions

The team made several assumptions to limit the scope of the task and provide a reasonable basis for comparison of alternate solutions. These include degradation of current UAV operational capabilities, modifications to the air vehicle, the effect on normal UAV flight parameters and operations, and representations of the UAV systems used in this study.

a) No Degradation of Current UAV Operational Capabilities

Proposed modifications to the UAVs do not significantly adversely impact current operational modes, parameters, capabilities, or readiness. The stakeholders were willing to accept a 25 percent reduction in performance to accommodate weapon integration.

b) No Modification to Air Vehicle

Any proposed solution would require no major modifications to the UAV airframe itself. For the purposes of this study, the airframe was assumed to be physically and mechanically capable of transporting the entire payload (sensors and weapons) within normal operational boundaries. Minor mounting holes were considered acceptable and necessary electrical connections possible without major modification.

c) Normal UAV Flight Parameters and Operations

The UAV will maintain its normal operating procedures, flight parameters, and limits. The operator was asked to perform additional tasking; however, the UAV was operated within the same flight envelope.

d) Surrogate Representation Adequate for Study

The proposed surrogate representations of the two UAVs addressed in the study were considered adequate. The study was intended to incorporate broad weapons

concepts for all in the man-portable and tactical UAV variations within a tier, without make or model specifics.

2. Limitations and Constraints

Several limitations and constraints were identified and in place for the duration of the project. These included keeping the classification of the document to Unclassified, limiting the UAS surrogate models to two generic variants, time restrictions of the study, and legal implications of arming a UAV. The following sections discuss these in further detail.

a) Classification

The Team realized that incorporation of exact specifications could result in the release of sensitive information. As a result, no exact specifications are included in this report. Instead, generic representative values obtained from open source literature were used. Any resulting solution remains unclassified. To ensure no accidental information disclosures, classification guidelines for included technologies were obtained and reviewed. All documentation generated was reviewed frequently by SME to ensure no inadvertent disclosures.

b) Limited UAS Models

Twelve representative UAVs were identified in Table 4. Rather than attempt to address every possible variant of these UAV with their subtle differences, generic representations of a man-portable and tactical UAV were created. Only these two representations were used in the study.

c) Time

The time available for completion of the study is fixed: approximately eight months. Team schedules need to be adjusted to allow adequate time to participate in the various facets of the project.

d) Legal Issues

There has been some concern by the Team that certain arming aspects of UAV may be prevented by International Law or treaties. The Intermediate-Range Nuclear Forces Treaty Article II between the U.S. and the Soviet Union addresses "ground-launched cruise missiles" with a range capability of 500 to 5,500 kilometers

(Gormley and Speier 2003). The team is aware of this issue. As the project is a study only with no actual deployment planned, this possible constraint did not affect the study.

D. Path Forward

By some estimates, there are currently several thousand UAS in theater in Iraq and Afghanistan. The majority of these devices are capable of being operated at the local company/platoon/squad level rather than under theater control. Many of these devices are not being fully utilized due to limitations in the performance of the currently fielded equipment (DoD 2009). Advancements in technology realized since their initial development may provide means for extending the operational utility of these UAS, increasing their usefulness to the warfighter in the C-IED mission by providing a more efficient and effective capability. Given a better equipped, more robust, and more flexible local UAS capability, the warfighter can develop more proactive IED interdiction tactics.

THIS PAGE INTENTIONALLY LEFT BLANK

II. PROBLEM DEFINITION

The Problem Definition phase defined the scope and boundaries of the analysis to be performed and resulted in the generation of system level requirements and a system architecture. Needs analysis was the first major event and consisted of performing stakeholder and existing capability identification and analysis, development of representative mission scenarios, and defining the constraints and limitations applicable to the project. These activities resulted in a refinement of the problem statement, a set of system requirements, a hierarchy of objectives, determination of the system boundary, functional analysis, and development of measures of performance and related key performance parameters. Finally, an architecture to be used in the accomplishment of the project was developed.

A. Needs Analysis

Stakeholders and their inputs served as the starting point for the Needs Analysis, but additional investigations and analyses were required to begin developing solutions that meet the true needs of the stakeholders. A capabilities assessment was performed to understand the strengths and weaknesses of current systems in a C-IED role. Additionally, Concept of Operation (CONOPS) and engagement scenarios were developed to define an operational context and limit the scope to a manageable level for analysis. Finally, it was necessary to understand the mission requirements, identify the constraints and outline the assumptions that were used to establish boundaries for the problem. Through these processes, it became apparent that the primitive need of the C-IED with UAS problem might be addressed by developing enhancements for UAS that improve the capabilities to defeat IEDs and/or the IED placement teams.

1. Stakeholders

The Roving UAV IED Interdiction System (RUINS) team researched various organizations that had interest in UAS and C-IED to locate potential stakeholders for the project. Contact was established through telephone calls, emails, and meetings. These initial discussions helped shape the initial problem statement and eventually led to contacts

within the stakeholder organizations. The contacts also provided feedback to questionnaires designed to rank the importance of potential MOEs and MOPs.

a) Stakeholder Identification

The RUINS project has seven stakeholders. They have been divided into different levels according to their influence on a program. The primary stakeholders have the authority to make a program-changing decision if needed. Secondary stakeholders lack this authority, but are very important to the successful completion of the project due to their expertise in certain aspects of the project. The tertiary level stakeholders are not directly involved in the project, but do bring valuable insights to the approach to the project.

Three primary stakeholders have been identified. They include the C-IED Technical Program Office (TPO), the Precision Attack Weapon System (PAWS) TPO, and the Irregular Warfare (IW) TPO.

Three secondary stakeholders were asked to provide inputs to the project. All three are certified UAV pilots who train others in proper UAV operation. Two are associated with tactical UAVs, and one is associated with man-portable UAVs.

The single tertiary stakeholder on the project is a systems engineer with many years of experience. His role was a subject matter expert (SME) for the Team. His long experience in accomplishing tasks such as the RUINS project is critical to the best results from the Team.

b) Stakeholder Analysis

Each of the stakeholders was sent a questionnaire containing a pair-wise ranking matrix including proposed MOEs and MOPs. At the same time, the relative importance of each of the primary stakeholders, and their relation to the project, was determined by the Team to best score the responses. The questionnaire responses were reviewed to develop a stakeholder ranking according to each stakeholder’s preferences. Stakeholder weighting derived by the Team was then applied to develop a final ranking of proposed MOE and MOP. These results are presented in Table 5 and Table 6.

Table 5 - MOE from Stakeholder Responses

Stakeholder Ranked Measures of Effectiveness				
Stakeholder	Counter IED	Irregular Warfare	PAWS	Final Ranking
Stakeholder Weight	0.37	0.30	0.33	
Target Identification	0.2470	0.1830	0.1270	0.1882
Maneuvering Target Strike	0.2113	0.0560	0.2100	0.1643
Reconnaissance	0.1757	0.1970	0.1200	0.1637
Surveillance	0.1400	0.1970	0.1050	0.1456
Stationary Target Strike	0.1043	0.0610	0.1810	0.1166
Flexible Capabilities	0.0687	0.2470	0.0330	0.1104
Covert Target Tracking	0.0033	0.0590	0.2230	0.1035

Table 6 - MOP from Stakeholder Responses

Stakeholder Ranked Measures of Performance				
Stakeholder	Counter IED	Irregular Warfare	PAWS	Final Ranking
Stakeholder Weight	0.37	0.30	0.33	
Data Link Performance	0.2450	0.1280	0.1960	0.1937
Target Tracking	0.1614	0.1030	0.2440	0.1711
Sensor Spectral Bands	0.2171	0.1480	0.1110	0.1614
Control Range	0.1057	0.2300	0.1080	0.1437
Sensor Resolution	0.0779	0.1870	0.1550	0.1361
RF Detection Threshold	0.1893	0.0640	0.0740	0.1137
Target Localization Error	0.1336	0.0910	0.0680	0.0992
RF Directional Resolution	0.0500	0.0500	0.0450	0.0484

To determine the effects of variations in the relative stakeholder rankings and their effects on the final MOE and MOP, a simple sensitivity analysis was performed. In a typical sensitivity analysis, each stakeholder response and stakeholder weight is varied, one at a time (Haskins 2007). The effect on the resulting ranking is noted for each change. In this analysis, the relative stakeholder ranking was applied to a different stakeholder's response preferences. Six possible ranking variations were investigated. It

was found that these variations had no effect on the final MOP ranking results. In the MOE results, an occasional ranking swap of two of the upper level measures, “Conduct Maneuvering Target Strike” and “Conduct Reconnaissance,” did occur. This swap was not surprising given the relatively equal ranking of those two measures.

2. Current C-IED Capabilities

"Tackling the IED threat is vital for us to make military progress. C-IED is not just about the bomb disposal expert defusing a bomb, as vital and dangerous that role is. It is about making sure our soldiers have a range of tools, tactics and techniques available to them." – United Kingdom Minister for Defense Equipment, Support and Technology, Peter Luff.

Current tactics for countering the IED threat are constantly evolving. Friendly forces develop countermeasures for particular types of IEDs. Meanwhile, the bomb makers are also developing and evolving their techniques as well. The following IED Defeat Framework from the U.S. Army Improvised Explosive Device Defeat Field Manual summarizes the best practices when dealing with IEDs.

From IED Defeat Framework (Department of the Army 2005):

> *Predict activities. These activities are used to identify and understand enemy personnel, equipment, infrastructure, [tactics, techniques, and procedures] TTP, support mechanisms, or other actions to forecast specific enemy IED operations directed against U.S. interests. This is driven largely by success in analysis in the requirements management. Predict activities assists in—*
>
> - *Identifying patterns of enemy behavior.*
> - *Identifying emerging threats.*
> - *Predicting future enemy actions.*
> - *Prioritizing intelligence, surveillance, and reconnaissance (ISR) missions.*
> - *Exploiting IED threat vulnerabilities.*
> - *Targeting enemy IED attack nodes (such as funding and supplies).*
> - *Disseminating alert information rapidly to specific users.*
> - *Analyzing forensics and enabling better on-scene technical analysis.*
>
> *Detect activities. These activities contribute to the identification and location of enemy personnel, explosive devices, and their component parts,*

equipment, logistics operations, and infrastructure in order to provide accurate and timely information. These actions assist in the efforts to interdict and destroy these activities. Detect activities aid in—

- *Detecting and identifying explosive material and other IED components.*
- *Detecting chemical, biological, radiological, and nuclear (CBRN) material.*
- *Recognizing suicide bombers.*
- *Conducting forensic operations to track bomb makers and/or handlers.*
- *Conducting persistent surveillance.*
- *Training to improve detection of IED indicators by digital means.*
- *Developing priority information requirements (PIR) tied to IED operations decisive points. Linking and synchronizing detection assets to PIR-related named areas of interest (NAIs). Using detection means across the full range available (from imagery, mechanical-clearance operations, search techniques, dogs, and so forth).*
- *Recognizing individual soldier actions and awareness in all activities.*

Prevent activities. These activities disrupt and defeat the IED operational chain of events. The actions focus on the target to interdict or destroy key enemy personnel (bomb makers, leaders, and financiers), the infrastructure/logistics capabilities (suppliers and bomb factories), and surveillance/targeting efforts (reconnaissance and overmatch operations) before emplacement of the device. They also include actions to deter public support for the use of IEDs by the enemy. Prevent activities aid in—

- *Disrupting enemy operations and their support structure.*
- *Denying critical IED-related supplies to the enemy.*
- *Increasing awareness of enemy TTP and their effectiveness.*
- *Denying the enemy the opportunity to emplace IEDs (through presence patrols, observation posts, checkpoints, aggressive surveillance operations, and so forth).*
- *Rewarding local nationals' cooperation in determining the locations of caches, bomb making, or emplacing activities.*
- *Denying easily concealed locations (such as trash piles and debris along sides of primary routes) and removing abandoned vehicles along routes.*

Avoid activities. These activities keep friendly forces from IEDs when prevention activities are not possible or have failed. Avoid activities include—

- *Increasing situational understanding (SU) of the area of operations (AOs) and continually refining the common operational picture (COP) and the timely and accurate dissemination of related information.*
- *Ensuring timely and accurate status reporting and tracking.*
- *Altering routes and routines.*

- *Marking and bypassing suspected IEDs.*

Neutralize activities. These activities contribute to the destruction or reduction of enemy personnel, explosive devices, or supplies. They can be proactive or reactive in nature.

- *Proactive activities include conducting operations to eliminate or interrupt the enemy's leaders, suppliers, trainers, enablers, and executors responsible for the employment of IEDs against coalition forces.*
- *Reactive activities include conducting controlled detonations or render safe procedures (RSPs) against identified IEDs, caches, captured enemy ammunition (CEA), and so forth. Explosive ordnance disposal (EOD) forces are the only personnel authorized to render safe IEDs.*

Protect activities. These activities improve the survivability of IED targets through hardening, awareness training, or other techniques. Protect activities include—

- *Disrupting, channeling, blocking, or redirecting energy and fragmentation.*
- *Creating greater standoff distances to reduce the effect that IEDs have on their intended targets.*
- *Incorporating unmanned platforms.*
- *Using jamming devices.*
- *Reducing time and distance in which intended targets are within IED range.*
- *Accelerating processes and increasing the effectiveness by which reaction and evacuation operations are conducted.*
- *Providing blast and fragmentation mitigation for platforms, structures, and personnel.*
- *Avoiding establishing patterns and predictable forms of behavior.*
- *Conducting proper pre-combat inspections (PCIs) and rehearsals for all operations.*
- *Treating every operation as a combat mission (from a simple convoy to daily forward operating base (FOB) security).*

Unmanned aircraft can be used in all areas of the framework. A UAV can be used to monitor suspected bomb-makers to predict their activities. UAV can be used to detect IEDs once they have been emplaced. Prevention can be accomplished through increased surveillance. Once the IED has been located by a UAV, friendly forces can avoid it or act to disarm it. IEDs can be neutralized by a UAV either by targeting the bomb-makers

before they have a chance to act or by rendering the emplaced IED safe. UAV can carry jamming devices ahead of a supply convoy to protect it. Providing an armed UAV at the squad level may give them the extra tool needed to prevent or neutralize the IED.

3. IED Defeat Capabilities

There are several methods of IED defeat in the field today. Devices currently in the field serve to either detect IEDs to allow neutralization prior to detonation or help minimize the effects due to detonation. The methods currently employed are jamming, route clearing, neutralization, detecting explosives, EOD, and protection for vehicles and personnel.

Commonly used C-IED devices are the Joint Counter Radio-Controlled Electronic Warfare (JCREW) Systems. These systems are commonly employed on the ground, either mounted on vehicles or as part of a man-portable system. These systems prevent radio-frequency (RF) controlled IEDs from detonating by jamming communications. They cover a wide spectrum of threat frequencies but may also disrupt friendly communications and datalinks. These Electronic Warfare (EW)-based systems provide localized protection and do not depend on actually detecting IEDs. This means there are still significant dangers to friendly forces and civilians. A UAV system could augment the JCREW systems by providing alerts to potential IED locations through alternative methods, such as laser designation or paint marking that could easily be seen by ground forces.

The Vehicle Operated Sensor System (VOSS) supports the C-IED mission by providing increased situational awareness. VOSS is a ground vehicle-based system with a stabilized camera, which is mounted upon a 25-foot mast. While the mast-mounted camera provides some localized detection capability for the vehicles within the convoy, the mast mounted system is very visible and acts as a beacon to the enemy.

A UAV-mounted camera could provide wide-area detection coverage prior to entry by a vehicle convoy. An added benefit of the UAV over the mast mounted system is that the UAV system is more covert.

4. Existing UAS Capabilities

The idea of using a UAV to support the C-IED mission is not new. There are several C-IED UAS such as the Sky Warrior Alpha, Sentinel Hawk, MQ-5B Hunter, Copperhead, and Yellow Jacket. These UAS employ infrared sensors used for route-directed cooperative UAV surveillance, radar systems to detect specialized threat returns, and full-motion video to directly control vehicles (Simpson 2009). However, the main focus of these systems is surveillance. Therefore RUINS focused specifically on possible weapon technologies for use with the Tier I (man-portable) and Tier II (tactical) UAV without removing existing UAV capabilities. The investigation utilized surrogate representations of the two UAV tier groups with representative sensor performance, flight characteristics, and physical parameters.

a) Man-Portable UAS Capabilities

Tier I UAS, or Man-Portable UAS, are already being used in Afghanistan and Iraq. Many of the small UAV have optical systems, but little else, as they are largely used in an ISR type function. Table 7 lists the physical properties of these Tier I UAVs in theater. The most commonly used Tier I systems are:

- Raven – Generally used for aerial intelligence, surveillance, target acquisition, and reconnaissance. The Raven uses a Charge-Coupled Device (CCD) color video camera or an infrared night vision camera for Day/Night capability.
- Cutlass – Developed to provide ISR, the Cutlass uses a steerable low-light camera that interfaces to a real-time video tracker to provide target tracking.
- Wasp – Designed for Reconnaissance, Surveillance, Target Acquisition (RSTA) and Battle Damage Assessment (BDA), the Wasp uses several miniature Electro-Optic (EO) video-cameras.
- Puma – An upgrade to the Pointer UAV, the Puma employs two EO/IR cameras for surveillance.

Table 7 - Most Common Tier I UAVs

Vehicle	Wingspan (in.)	Length (in.)	Horizontal Speed (knots) (max, cruise)	Ceiling (feet)	Endurance (hours)	Max Payload (lbs)
Cutlass[1]	55.2	32.6	85, 65	unavailable	1	3
Raven[2]	54	36	44, 17	500	1 to 1.5	unavailable
Wasp[2]	28.5	15	31, 22	1,000	0.75	unavailable
Puma[2]	110.4	55.2	40, 20	500	2	unavailable

1. Refers to all Cutlass data (L3 Communications 2009)
2. Refers to all Raven, Wasp, and Puma data(AeroVironment, Inc. 2010)

The Tier I surrogate was defined by averaging the physical parameters of the UAVs in Table 7. Although the AeroVironment manufactured UAVs (Raven, Wasp, and Puma) do not advertise any payload capability, the Tier I operators that Team Bravo contacted claimed small payload integration efforts up to 1.5 to 2.5 lbs. The Tier I surrogate UAV is defined in Table 8.

Table 8 - Tier I Surrogate UAV

Wingspan (in.)	Length (in.)	Horizontal Speed (max, cruise) (knots)	Ceiling (feet)	Endurance (hours)	Max Payload (lbs)
62	34.7	50, 31	500	1.3	2.5

b) Tactical UAS Capabilities

Tier II UAS, also known as Tactical UAS, "fill the capability gap between the short range mini-UAVs and the long range, extended endurance [Medium Altitude Long Endurance] MALE and [High Altitude Long Endurance] HALE UAVs, combining the flexibility of the smaller platforms with the longer endurance of the higher-end platforms" (Thales n.d.).

Most Tactical UAS are still only used for Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) purposes. Common payloads include optical payloads such as an infrared camera, and a daytime television (TV) camera with a selectable near-infrared filter, and often employ a laser pointer to aid in targeting.

Team Bravo utilized the same approach to identify the Tier II surrogate UAV as implemented for the Tier I UAV. The team researched the physical properties of the most commonly operated UAVs in Afghanistan and Iraq. The properties are listed in Table 9. The Israeli Aerospace Industries (IAI) POP-300D sensor was considered to be the sensor package for this Tier. This sensor package provides an inertially-stabilized platform for the multiple field of view (FOV) 3–5 μm IR and visible optical sensors. In addition, the sensor package includes an optically bore-sighted laser target designator system, compatible with many U.S. weapon systems, as well as an eye-safe laser range finder (Israel Aerospace Industries 2009).

Table 9 - Most Common Tier II UAVs

Vehicle	Wingspan (in.)	Length (in.)	Horizontal Speed (max, cruise) (knots)	Ceiling (feet)	Endurance (hours)	Max Payload (lbs)	Max Take-off Weight (lbs)
RQ-7 200[1]	244.8	141.6	90, 65	15,000	8 to 9	45-80	327
RQ-7 400[1]	201.6	150	85, 65	11,000	5	75	448
RQ-7 600[1]	268.8	188.4	80, 65	16,000	12 to 14	91	584
Tarzan[2]	216	129	unavbl, 43	14,000	unavbl	105	unavbl
TigerShark LR3[3]	204.7	187	unavbl, 65	unavbl	9.5	150	unavbl
Sentry HP[4]	153.6	101.04	75, unavbl	16,000	8	75	325
Pioneer[5]	201.6	168	99, unavbl	15,000	4.5	99	448

1. Refers to all RQ-7 200, 400, and 600 data (AAI Corporation 2010)
2. Refers to all Tarzan data (Theiss Aviation 2010)
3. Refers to TigerShark LR3 data except payload (Flightglobal 2010)
4. Refers to all Sentry HP data (Wikipedia 2010)
5. Refers to Pioneer data except payload (Parsch 2007)

The surrogate Tier II UAV was defined by averaging the physical parameters of the UAVs in Table 9. Although the TigerShark LR3 and Pioneer UAVs did not have defined payloads in their respective references, the SMEs and UAV operators contacted by Team Bravo had estimated 150 lbs and 99 lbs respectively. Team Bravo used the Tier II surrogate UAV physical parameters as defined in Table 10.

Table 10 - Tier II Surrogate UAV

Wingspan in.	Length in.	Horizontal Speed (max, cruise) (knots)	Ceiling (feet)	Endurance (hours)	Max Payload (lbs)	Max Take-off Weight (lbs)
213	152.1	85.8, 63	14,500	7.83	92.96	426.4

5. UAS-Based C-IED CONOPS

Tactical and man-portable UAS platforms are already being used to provide ISR capabilities to U.S. ground forces. Weaponizing these types of UAS would provide a quick strike capability to eliminate IEDs and the personnel responsible for placing and detonating IEDs while maintaining their current ISR capabilities. The envisioned CONOPS for UAS-based C-IED would be a modification to current ISR CONOPS.

Launch and recovery would maintain commonality with traditional ISR operations. Expected differences would include loading the weapon onto the UAS prior to launch and performing any additional preflight checks. The UAS would be brought to an ordnance loading location where the weapons would be attached after having their mission parameters programmed. It would then be transported to the launch area and loaded onto the launcher (for Tactical UAS). The weapon would be armed just prior to launching the UAS. Recovery after a mission where the weapon was not fired could require modifications to the recovery system. These would depend on the size of the weapon relative to the UAS.

Weapon handling procedures would maintain commonality to manned platform operations. In cases where the weapon was not traditionally used in an air-to-ground fashion, new procedures will be developed. These procedures would be drawn from the best practices of similar airborne weapons handling.

For a weaponized system, the UAS would be loaded with a pre-planned route to patrol and provide real-time situational awareness back to the ground station. The UAS sensor package would then search along the pre-planned route to detect and track potential

targets. The tracked targets would be identified and confirmed by the ground station operator. This portion of the mission would be identical to a traditional ISR mission.

If a potential target is found, the operator would designate the target using the ground control station. Movement to the target could be accomplished by placing an additional waypoint into the flight plan. The location of this waypoint may need to move dynamically for rapidly moving targets. The UAS would then autonomously navigate to an appropriate launch area for the weapon to be employed. Rules of Engagement (ROE) procedures follow with consent to fire under human control culminating in the desired outcome: employing a lethal or non-lethal weapon to neutralize the IED threat.

Should a weapons deployment using the weaponized UAS not be approved by the firing authority, the UAS would continue to maintain track on the target and provide target location data to Command and Control (C2). C2 would then command EOD or another response team to address the IED threat. After engagement of the IED threat by friendly forces, the UAS would provide imagery data for BDA by the ground station crew. After the IED threat had been neutralized, the UAS would resume normal ISR operations.

Figure 4 - RUINS OV-1

To evaluate the operations and effectiveness of proposed UAS-weapon solutions developed during the project, representative targets and scenarios were developed by incorporating suggestions and preferences provided by stakeholders. The developed scenarios were also used in identifying important modeling parameters and additional considerations necessary for the use of RUINS that may have been overlooked in earlier analysis. While primary emphasis was placed on the successful engagement of the targets, collateral damage, timing, and cost were also considered during the evaluations.

Figure 5 outlines the notional operations and interactions that take place during the mission scenarios where the ground control station commands a UAV to engage a target with a weapon. It is assumed the imagery being fed to the ground control station is of sufficient quality for the human operator to detect and identify the target. It is also assumed that the weapon provides sufficient effectiveness to kill the target.

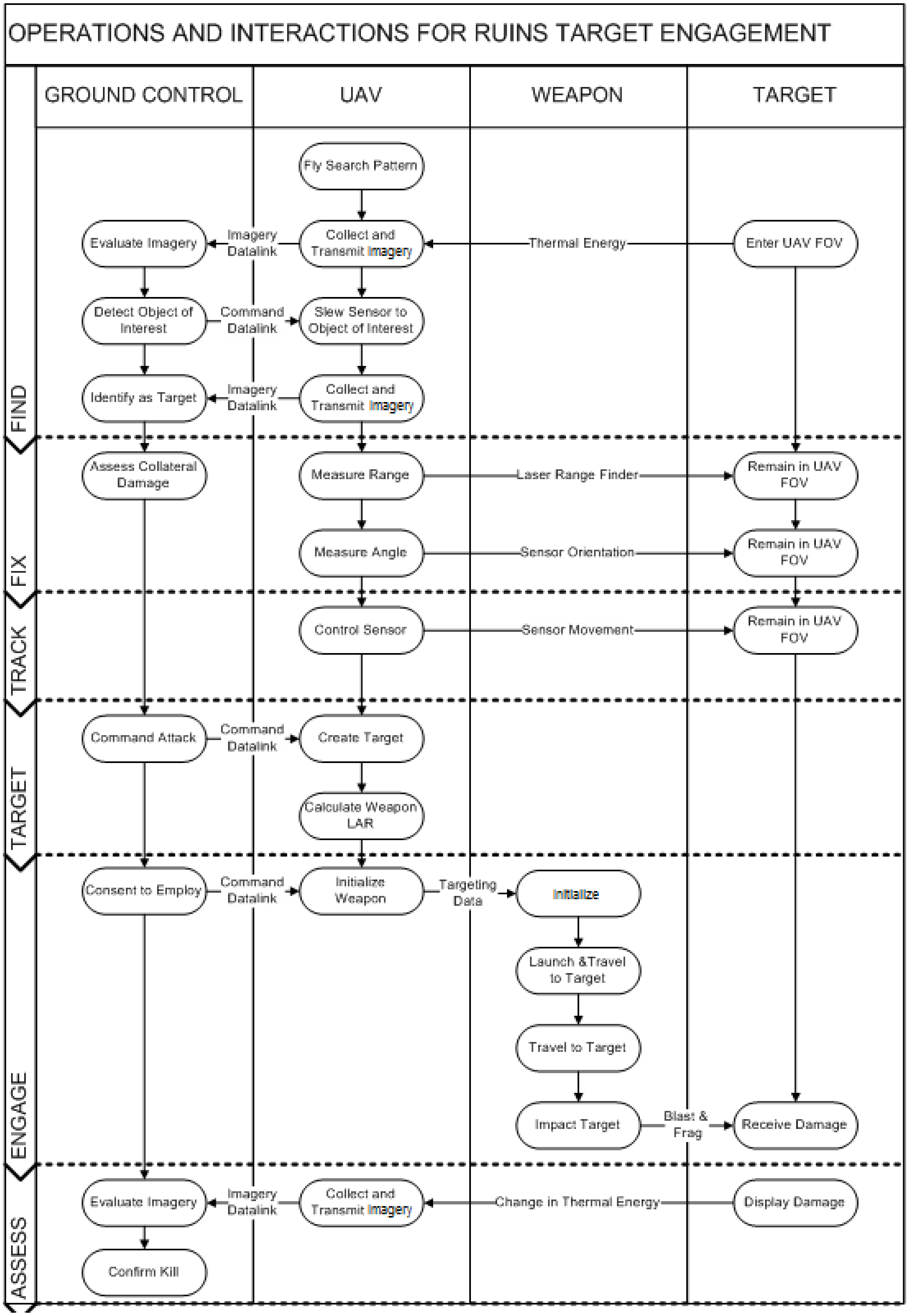


Figure 5 - System Operations and Interactions for RUINS Target Engagement

B. Scenario Development

Two types of targets were used in the analysis. The different vulnerabilities of the targets provide for the broad examination of weapon capabilities needed for this initial investigation. Both targets, while related to the C-IED mission, are also representative of the types of targets an armed UAV may engage in other mission types.

1. Targets

a) IED Emplacement Team.

Three persons were used in the representation of an IED emplacement team. These persons were unprotected by any armor or protective gear. Two were considered actively engaged in actual IED emplacement: kneeling, facing each other, and separated by approximately three feet. A non-active IED was being assembled on the ground between them. While not yet activated, the explosive of the IED could be detonated by the effects of an offensive weapon. The third person was serving as a lookout, and was standing approximately eight feet from the center of the other two persons. Weapons utilized against this type of target were lethal.

b) (2) Light Vehicle.

A separate target was required for evaluating the effectiveness of the UAV-weapon system against a lightly armored vehicle. The target was considered to be a transport vehicle utilized by those engaged in the implantation of IEDs. The vehicle did not need to be destroyed for success, but must lose its mobility. The target was represented by a small standard half-ton pickup.

2. Scenarios

a) Fixed Threat Scenario

Scenario 1 considered a fixed target. A fixed IED threat, represented by the IED emplacement team target, was assumed to be positioned at the red triangle. The RUINS operator was assumed to be at least five kilometers away. UAV flight altitude was assumed at elevations of 100 and 500 feet above ground level (AGL) for the Tier I UAV, and 500 and 2000 feet AGL for the Tier II UAV. The UAV was dispatched to the target location from random locations in its ISR path, allowing differing targeting times. Different airspeeds were used for each Tier: 30 knots for the Tier I UAV, 65 knots for the

Tier II UAV. A single time of day, noon, was simulated. Other particulars concerning the engagement are included in Table 11.

Table 11 - Stationary Target Scenario

Scenario 1: STATIONARY TARGET SCENARIO	
Purpose:	Simulate armed UAS interdiction against a stationary target with elevated risk of collateral damage.
Domain:	Medium-sized city in arid environment (3 story buildings or less, populated areas, narrow dirt streets)
Constraints:	1.0. Use of representative UAS Tier II or below. 2.0. Cost 3.0. Timeframe 4.0. Policy
Assumptions:	1.0. Locally controlled UAS dispatched to scene. 2.0. Local UAS flown under primary computer control with internal algorithms to handle control dropouts. 3.0. Friendly forces are a minimum 15 minutes away from target location by ground vehicle. 4.0. Local UAS control a minimum 5 km from the suspected IED site. 5.0. Medium-sized city, buildings three stories or less, primarily two lane or less dirt streets. 6.0. Low wind (< 10 kts) 7.0. Temperature 90° F. 8.0. Noon local time. 9.0. UAS has been launched, traveling at 30 kts for Tier I and 65 kts for Tier II.
Scenario:	1.0. Urban UAS IED Placement Interdiction.
Vignettes:	1.0. Engage targets using lethal weapons.

Figure 6 illustrates the first scenario in an urban environment. A RUINS performing an ISR mission over a relatively large city under local control spotted a group of persons, represented by the IED emplacement team target, acting in a suspicious manner. Upon further examination, it appeared the suspects were engaged in the implantation of an IED in a street. The RUINS maintained an observation of the suspects while further directions and engagement authority were obtained. As the potential IED was located in a populated area, there was heightened risk of collateral damage.

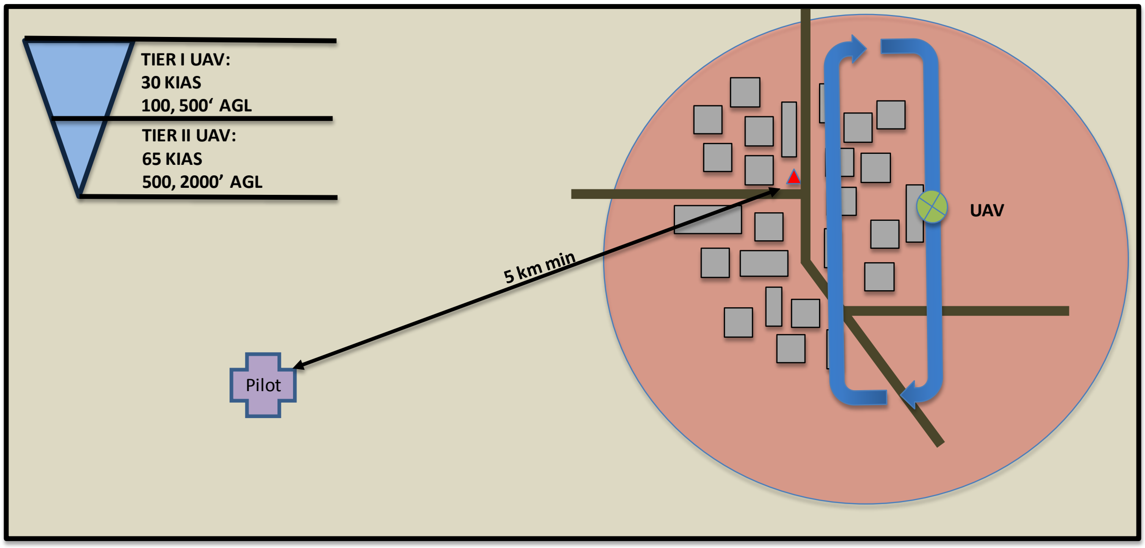


Figure 6 - Fixed Target Scenario

This scenario offered several challenges to the UAV-weapon and target engagement, including:

- Targeting accuracy
- Engagement timelines
- Weapon lethality footprint
- Collateral damage
- Possible loss of UAV control and/or operator feedback

b) Moving Threat Scenario

Scenario 2 considered a moving target. In this scenario, intelligence had identified a moving target that must be stopped. It need only experience a mobility kill, as it is desirable to capture those inside alive. A RUINS performing an ISR mission was dispatched to halt the target, represented in this scenario by the light vehicle target. The assumed vehicle speed is 40 knots. The vehicle is traveling down curving roads in relatively flat desert terrain. The target vehicle is in a rural environment, resulting in reduced risk of collateral damage.

This scenario offers its own set of problems for the UAV-weapon and target engagement, including:

- Targeting accuracy.
- Engagement timelines.
- Weapon lethality footprint.
- Weapon guidance capability (if any).
- UAV autonomous target tracking capability (if any).
- UAV flight capabilities.

Table 12 - Moving Target Scenario

Scenario 2: MOVING TARGET SCENARIO	
Purpose:	Simulate armed UAS engagement against a moving target with lower risk of collateral damage.
Domain:	Rural arid environment (little population, few buildings, winding dirt roads)
Constraints:	1.0. Use of representative UAS Tier II or below. 2.0. Cost 3.0. Timeframe 4.0. Policy
Assumptions:	1.0. Locally controlled UAS will be dispatched to scene. 2.0. Local UAS is under primary man control with internal algorithms to handle control dropouts. Algorithms are TBD. 3.0. Friendly forces are minimum 15 minutes away. 4.0. Local UAS control is five kilometers from current target position. 5.0. Rural arid environment, few buildings, narrow winding dirt roads. 6.0. Low wind (< 10 kts) 7.0. Temperature 90°F. 8.0. Midnight or noon local time. 9.0. UAS has been launched and is airborne, traveling at 30 kts Tier I, 65 kts Tier II. 10.0. Suspect vehicle velocity of 40 knots.
Scenario:	1.0. Rural UAS Moving Target Interdiction.
Vignettes:	1.0. Engage target using lethal weapons.

Figure 7 illustrates the second scenario. The target was again represented by the red triangle and was moving in the direction indicated. The RUINS operator was assumed to be at least five kilometers away. The UAV flight altitude was assumed at

elevations of 100 and 500 feet above ground level (AGL) for the Tier I UAV, and 500 and 2000 feet AGL for the Tier II UAV. The UAV was dispatched to the target location from random locations in its ISR path, allowing differing targeting times. Different airspeeds were used for each Tier: 30 knots for the Tier I UAV and 65 knots for the Tier II UAV. The simulation used noon as the time of day.

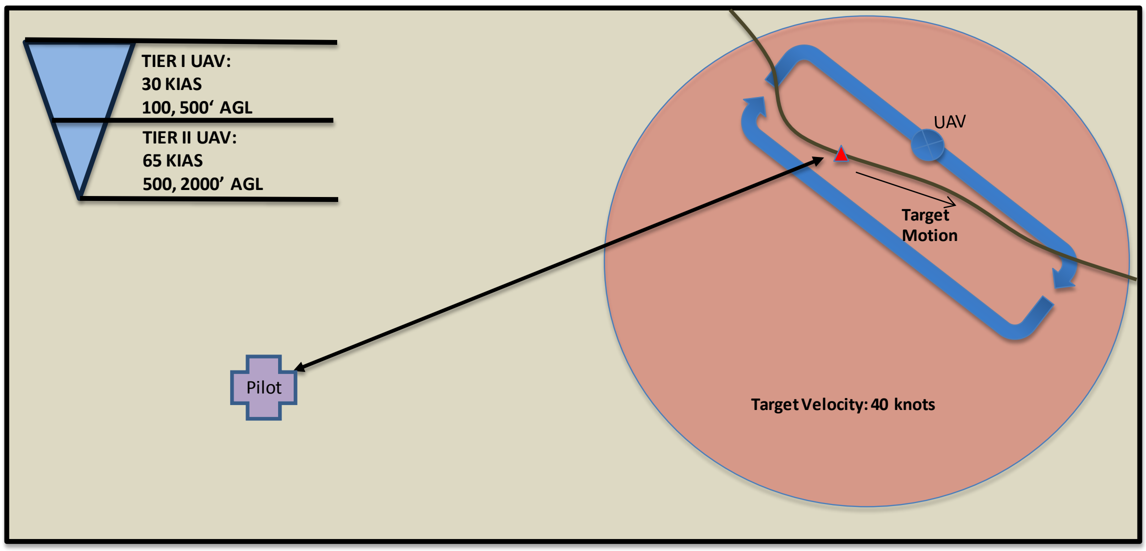


Figure 7 - Moving Target Scenario

C. System Requirements

Current events in Iraq and Afghanistan dictate a need for Coalition forces to adapt to the increasingly dangerous, changing, adversary. The adversary seeks to endanger the Coalition forces by placing and triggering camouflaged IEDs to inflict harm. The capabilities to prevent emplacement of or destroy IEDs are required for the C-IED effort. One solution to gain these capabilities is equipping the UAV with an offensive weapon. Requirements must be developed to bring these capabilities to fruition.

In developing system requirements, input was sought from the stakeholders on what was needed to aid the C-IED effort. Information was also gathered from the IED Defeat Framework (Department of the Army 2005) on what was needed to detect IED, prevent IED, and neutralize enemy forces to help protect the American Coalition forces.

Additionally, the Fed Biz Ops RFI Solicitation Number: W31P4Q-10-R-0142 (Fed Biz Ops 2010) provided an additional example of the aspects that should be considered when weaponizing a tactical UAV. The information captured the key aspects of UAS weaponization that RUINS project must address in the Design and Analysis phase. Top level requirements were developed based on the needs analysis and the information acquired from the above sources. Both functional and non-functional requirements were addressed for the UAS weapon system. The following list defines the common terminology used throughout the requirements:

- UAS Air Vehicle – The air vehicle component of the existing UAS.
- UAS Operator Squad – The ground team that is in charge of programming, launching, controlling, and recovering the UAS Air Vehicle.
- UAS Weapon System – The weapon and any necessary mounting adaptors, launchers/ejectors, wiring/cables, or other hardware.
- Weaponized UAS – The existing UAS with the inclusion of the integrated UAS Weapon System.

1. Functional Requirements

UAS Weapon System Ground Operations plays a pivotal role prior to launching the aircraft. There are certain pre-flight procedures that need to be followed in order to verify that the weapon system is operational, armed safely and mission ready. There is always risk, but implementing proper protocol helps increase safety and lower risk. Weapon system ground operations include loading the weapon, running pre-flight operations, and arming the weapon prior to launch. The below requirements are based on the UAS weapon system ground operations.

1.0 *UAS Weapon System Ground Operations*

1.1 The UAS Weapon System shall be installed by the UAS Operator Squad during the standard pre-launch procedures.

1.2 The UAS Operator Squad shall provide necessary data to the UAS Weapon System during the pre-flight programming procedures.

1.3 The UAS Operator Squad shall perform all necessary system tests and safe and arm procedures for the UAS Weapon System prior to launch.

At the conclusion of pre-flight operations, and assuming everything checks out, the aircraft is ready to be launched. Currently the Tier II UAS may utilize a catapult launch system to take flight. To avoid altering the existing launch system, the weaponized UAS should not exceed its weight launch limits. Exceeding the launch limits may result in the UAS not taking flight and possibly crashing as a result. After the UAS has completed its mission, it needs to be able to be recovered safely. "Recovered safely" means aircraft intact along with any unused weapons. Currently the UAV can be recovered safely without the added weapon system. Therefore, it is imperative that it can do the same with the weapon system. Taking into account what the system needed to achieve and using the "RUINS Top Level Functional Hierarchy" Figure 18, the following requirements were derived.

2.0 *UAS Weapon System Launch and Recovery*

2.1 The Weaponized UAS shall be capable of being launched from the existing UAS launching system.

2.2 The Weaponized UAS shall be capable of landing and being recovered with unused weapons.

Prior to pre-ops, launch, and recovery, the weapon needs to be integrated onto the UAV. Integration is not just attaching a weapon to the side of an aircraft with nuts and bolts; there needs to be system-level integration with any data link systems, payloads, under-wing stores, Ground Control System, and weapon/store management system. System integration is needed to link together the subsystems and ensure that all the subsystems function together correctly in order to successfully complete its mission. The following requirements were derived in order to verify the proper integration of the weapon.

3.0 *UAS Weapon System Integration and Carriage*

3.1 The UAS Weapon System shall not exceed the payload limits of the UAS Air Vehicle.

3.2 The UAS Air Vehicle shall be certified for safe carriage and employment of the UAS Weapon System and shall maintain performance within its fully loaded flight envelope requirements.

3.3 The UAS Air Vehicle shall comply with the integration requirements defined in the Interface Control Document of the UAS weapon system.

3.4 The Tier 2 UAS shall be capable of carrying a single munition off axis without significantly affecting flight performance.

3.5 The UAS flight performance shall not be *significantly* degraded.

{The term "significantly" means changes of parameter values over more than an objective of 5 percent and threshold of 25 percent due to carriage of the weapon system.}

2. Non-Functional Requirements

Usability must be taken into account when selecting, designing, and integrating a system. The system must be designed for ease of use by making the human-to-machine interface simple. This is accomplished by minimizing training requirements while maintaining productivity, efficiency and safety. The Usability requirement is based on the constraints and boundaries that were established in the beginning of the project.

1.0 *Usability*

1.1 The Weaponized UAS shall not adversely impact existing functional capabilities of the UAS.

1.2 The UAS Weapon System shall require minimal additional training to be completed by the UAS Operator Squad.

D. Objectives Hierarchy

The key objective for the RUINS project was to decrease the IED threat using enhanced UAS capabilities. Figure 8 shows the breakdown of this main objective into two sub objectives: 1) Support C-IED Effort and 2) Maintain Operational Effectiveness.

The "Support C-IED Effort" objective was further decomposed to "Clear Supply Routes" and "Engage IED." "Clear Supply Routes" gauges the system’s ability to fulfill the role of an organic and persistent airborne capability. "Engage IED Targets" describes the impact that the RUINS system has on the C-IED mission by measuring weapon delivery effectiveness.

The "Maintain Operational Effectiveness" objective was decomposed to "Minimize Susceptibility" and "Measure Endurance and Performance Impacts on Aerial Vehicle." "Minimize Susceptibility" describes the engagement envelope of the RUINS system prior to enemy weapon range, and visual detection. "Measure Endurance Impacts" reflects the effects of integrated weapons on a UAS with regard to mission duration and range.

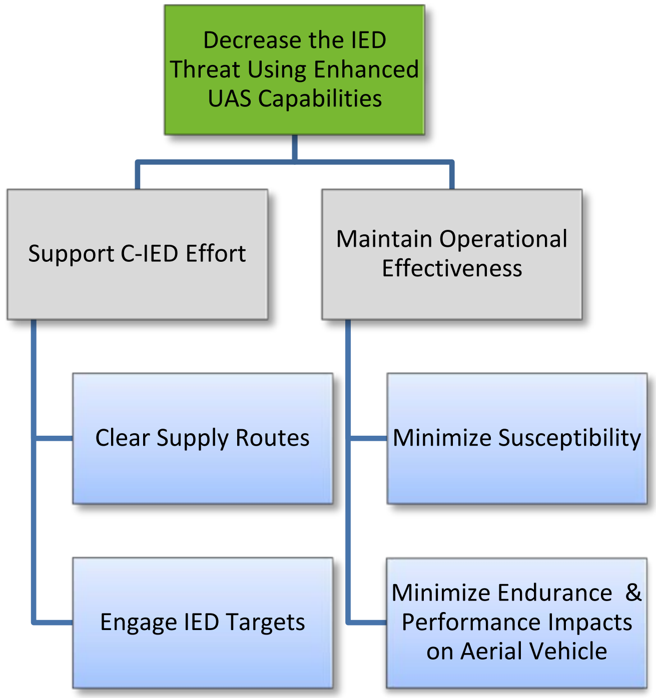


Figure 8 - Objectives Hierarchy

1. Measures of Effectiveness

The primary Critical Operational Issue (COI) that is impacted by the integration of weapons on a UAS platform is related to the system's need to be able to be lethal and disrupt the IED network. Therefore MOEs have been identified that are focused on this need. The Find, Fix, Track, Target, Engage, and Assess (F2T2EA) cycle, graphically illustrated by Figure 9, was used as the basis to derive the MOEs and MOPs that were used to assess the alternative designs. Find, Fix, Track, Target, and Engage were considered the Objectives.

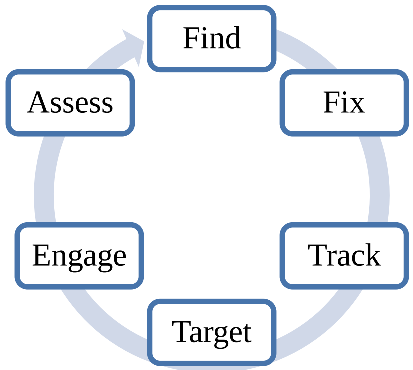


Figure 9 - F2T2EA Targeting Cycle

The Find, Fix, and Assess piece of the kill-chain were considered existing capabilities of the baseline UAS and its normal ISR mission. These functions were not assigned MOEs and MOPs under the assumption that integrating weapons will not interfere with the baseline capability of the platform, except for decreases in endurance, which are accounted for under a separate MOE/MOP. After consulting with the stakeholders and the Joint IED Defeat Organization (JIEDDO) mission, the following set of MOEs and MOPs was developed. The JIEDDO's mission is to: Detect the IED, Disrupt the IED Network, and Train Personnel. Training personnel is omitted from the RUINS objectives because it is a subset of the C-IED mission, whereas the focus for RUINS is to Detect and Disrupt IED. Following is a decomposition of the RUINS objective hierarchy into MOEs and MOPs that will be used to define Key Performance Parameters.

The first level is considered the mission: Decrease the IED Threat Using Enhanced UAS Capabilities. Objectives are the second level and represent the functions necessary to facilitate the mission. MOEs reside in the third level and correspond to accomplishment of mission objectives and the achievement of desired results (DAU 2010). The MOEs are further broken down into MOPs in the fourth level to specifically quantifiable features. The MOPs will be used to further define the Key Performance Parameters.

Mission: Decrease the IED Threat Using Enhanced UAS Capabilities

OBJ 1.1 Support C-IED Effort

MOE 1.1.1 Clear Supply Routes

MOP 1.1.1.1 Maximum Speed

MOE 1.1.2 Engage IED Targets

MOP 1.1.2.1 Minimum Range of Engagement

MOP 1.1.2.2 Maximum Effective Range of Engagement

MOP 1.1.2.3 Weapon Time of Flight

MOP 1.1.2.4 Weapon Miss Distance

MOP 1.1.2.5 Lethality Radius

MOP 1.1.2.6 Number of Stowed Weapons at Take-off

MOP 1.1.2.7 Weapon Minimum Acquisition/Track Range

OBJ 1.2 Maintain Operational Effectiveness

MOE 1.2.1 Minimize Susceptibility

MOP 1.2.1.1 Amount of Engagement Time Prior to Enemy Weapon Range

MOE 1.2.2 Minimize Endurance & Performance Impacts on Aerial Vehicle

MOP 1.2.2.1 Impact to Mission Time on Station

MOP 1.2.2.2 Impact to maximum UAV range

MOP 1.2.2.3 Impacts to maximum speed

E. System Boundary

Knowledge of all the system components that are involved and their interactions is crucial for early identification of issues and determination of system boundaries. The primary system of interest is the weapon system and its interactions with the target. The weapon system acts on the Target, indicating the Target is within the external system boundary.

The weapon representation shown in Figure 10 includes the actual weapon itself, any necessary fire control system, and any carriage/dispenser/mounting needed for the particular weapon chosen. The weapon system depends on the UAS for the initial physical transportation to the dispense location. The UAS uses inputs from GPS satellites

and its surrounding environment to successfully fly its ISR mission and locate possible targets. Course planning and UAS control will be supplied by the pilot through the Ground Control Segment, and UAS navigation and sensor systems will provide feedback to the Pilot on UAS and target position. Sensor systems contained in the UAS may also provide initial target positioning information to the weapon system, and the weapon system will provide status information to the UAS for operator feedback. The UAS may also interact with the target in an undesirable way, providing warning of its approach to the target in certain conditions though visible and audible cues.

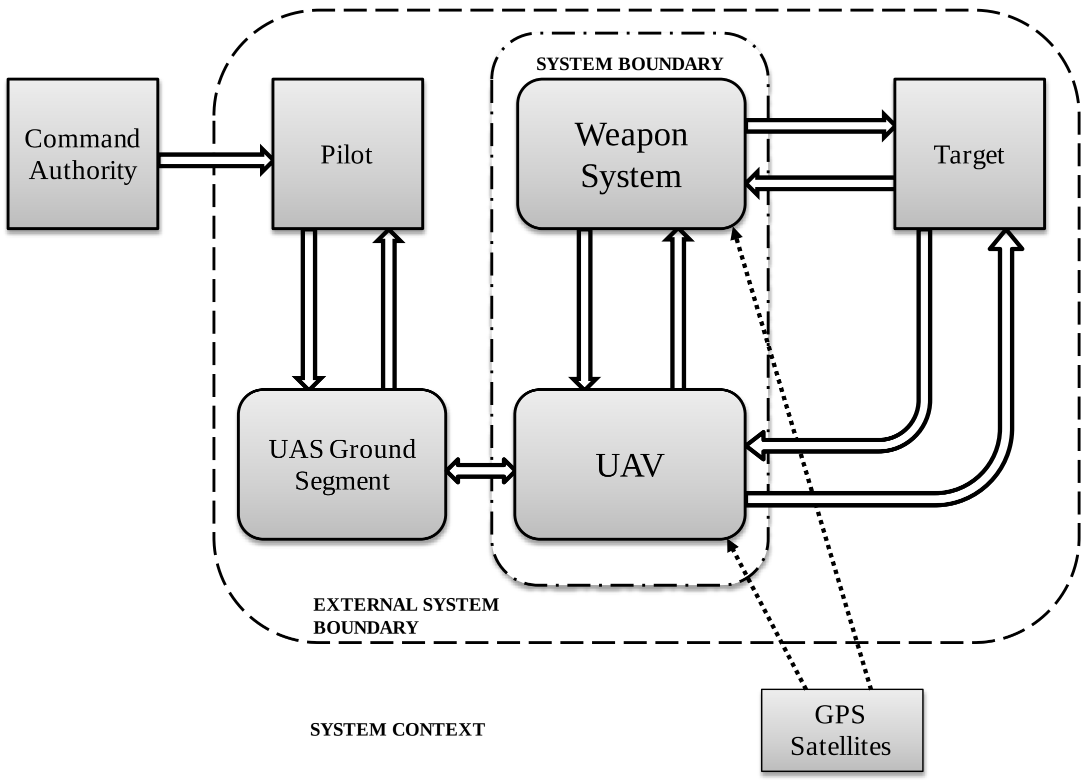


Figure 10 - System Physical Boundary Diagram

Depending on the type of weapon system, target positioning information may be derived directly from the target itself by the weapon system. Firing Command Authority will be provided through the Pilot, UAS Ground Segment, and finally UAV for issuance to the weapon system. Once deployed, the weapon may act directly on the target with no

further assistance from the UAS depending on the type of weapon used. It may continue to use GPS positioning as well as internally generated target positioning updates. While the Pilot and Ground Segment are outside of the RUINS boundary, the addition of weapons will place new requirements on them. The Pilot will require additional training to properly employ the weapons. The Ground Segment will require the ability to receive and display information from the weapon and to command the UAS to fire the weapon.

The RUINS complements and interfaces with several other activities in the battlespace. To depict how the RUINS makes use of other activities, an Integration Definition for Function Modeling (IDEF0) activity diagram was constructed. The A0 drawing depicts the boundary of the system under consideration in the study (Figure 11). The A-1 level drawing (Figure 12) depicts the interactions between the external activities and the RUINS and provides indications on required resources, both material and informational, required for successful RUINS operation.

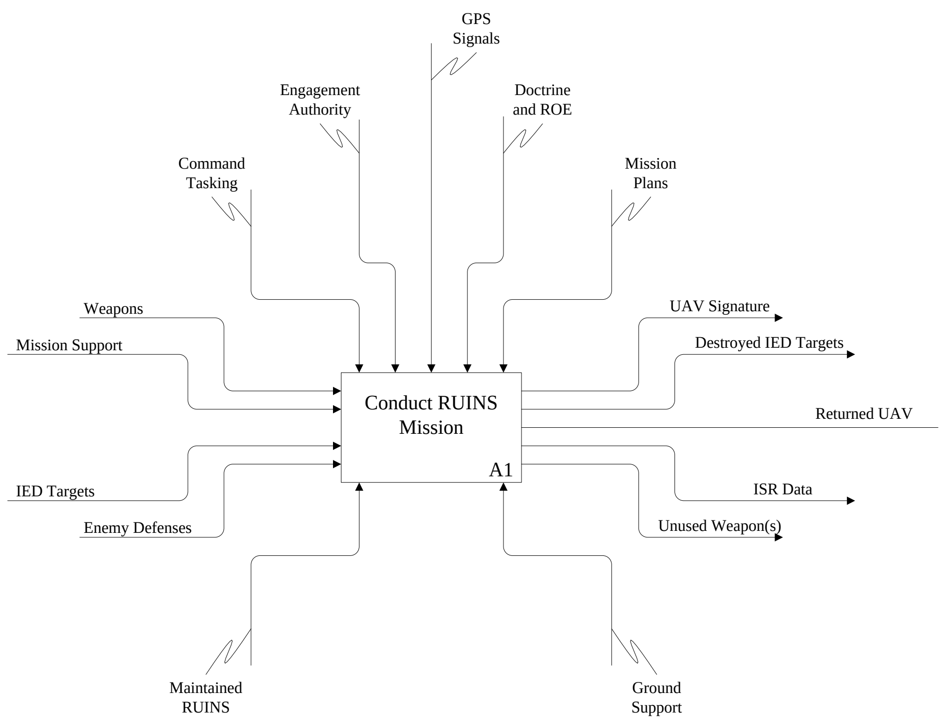


Figure 11 - RUINS A0 Diagram

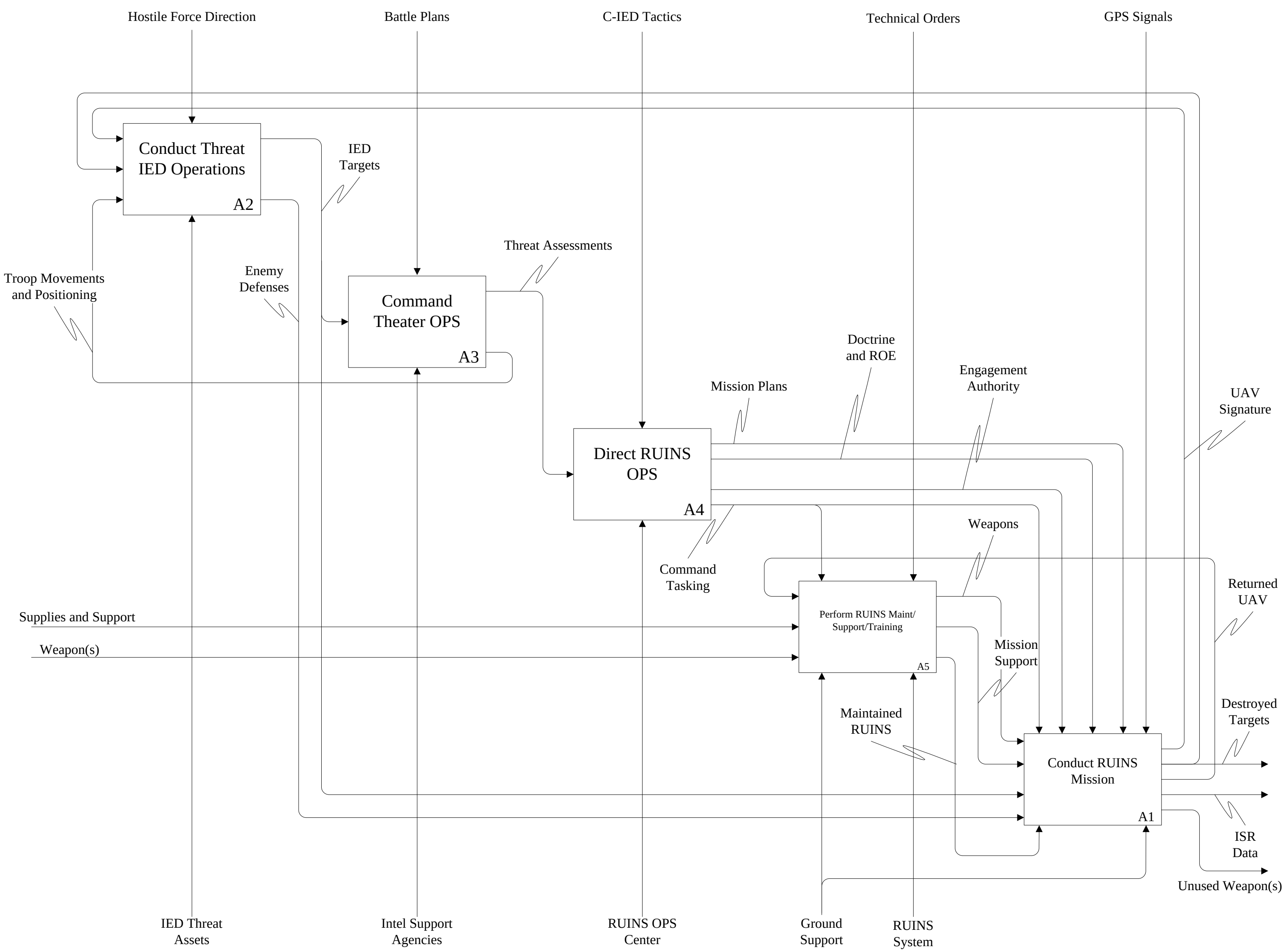


Figure 12 - System Context IDEF0 Diagram

F. Quality Function Deployment (QFD)

QFD was chosen as a method to ensure that the stakeholders' concerns and priorities would be reflected in the Team's analysis. This QFD effort was a team approach to transfer requirements into a technical solution. Customer requirements and preferences were defined and categorized as attributes, which were then weighted based on relative degrees of importance (Blanchard and Fabrycky 2006).

As used, the QFD focused on the specific characteristic needs and activities that would be used to evaluate weapons systems in the Analysis of Alternatives phase. With the Objectives and MOEs identified, four levels of QFD House of Quality (HOQ) matrices were developed to determine the weighting and relative importance of each objective. Then MOE were decomposed into Key Performance Parameters.

The first level HOQ emphasizes the system-level requirements. This matrix takes the primary needs and maps them to the "Hows." The "Hows" represent at least one technical solution for each identified customer need. The top five customer needs for RUINS were identified through a pair-wise assessment of 19 Counter-IED needs taken from a 2005 Army Field Manual (Department of the Army 2005) describing overall IED Defeat tactics. The team used stakeholder inputs and engineering judgment to conduct the pair-wise assessment.

Customer Needs	*Weights*		Clear Supply Route	Engage IED Targets	Minimize Susceptibility	Minimize Performance Impacts on Vehicle	
Objectives			Level	Level	Level	Level	
Organic Airborne Capability	**0.158**	0.258	**6**	**9**			
Persistent Airborne Intelligence Gathering	**0.101**	0.164	**6**		**9**	**9**	
Route Clearance/Overwatch	**0.085**	0.138	**6**	**6**	**6**	**6**	
Neutralize IEDs	**0.169**	0.276	**9**	**9**	**9**	**9**	
Project Targeted Force Beyond Visual Range	**0.101**	0.164	**6**	**6**	**6**	**6**	
Check Sum	**0.613**	1.000					
Goal Value							
Threshold Value							
Weighted Performance			6.8	6.6	5.8	5.8	25.0
Percent Performance			0.273	0.265	0.231	0.231	1.000 Check

Figure 13 - HOQ 1

Results from HOQ 1 reveal that the Objectives ranking is: Engage IED Targets, Clear Supply Routes, Minimize Susceptibility and UAV Performance Impacts. These are the most important objectives for fulfilling the mission.

The second level HOQ identifies the functions necessary to accomplish the RUINS mission. This HOQ, shown in Figure 14, is comprised of a pair-wise comparison between the Objectives identified in HOQ 1 and functions indirectly necessary to accomplish the mission. The purpose of this HOQ is to weigh the system functions necessary for mission success.

Objective	Weights		Detection of IED Activities	Effective Engagement	Timely Engagement	Accurate Weapons	Fix Target Location	Minimize Impact to ISR Mission	Minimize Availability Impact		
Clear Supply Route	**0.273**	0.273	**6**	**6**	**6**	**6**	**6**	**6**	**6**		
Engage IED Targets	**0.265**	0.265	**6**	**9**	**9**	**9**	**6**	**6**	**6**		
Minimize Susceptibility	**0.231**	0.231	**6**	**6**	**6**	**6**	**6**	**6**	**6**		
Minimize Performance Impacts on Vehicle	**0.231**	0.231	**9**	**9**	**9**	**9**	**9**	**9**	**9**		
Check Sum	**1**	1.00									
Goal Value											
Threshold Value											
Weighted Performance			6.7	7.5	7.5	7.5	6.7	6.7	6.7	49.2	
Percent Performance			0.136	0.152	0.152	0.152	0.136	0.136	0.136	1.000	Check

Functions

Figure 14 - HOQ 2

The highest weighted functions that support the RUINS mission are those that support IED threat neutralization followed by the original UAV functions that support the original mission of ISR.

The third level HOQ, shown in Figure 15, weighs the design characteristics that are necessary to perform the functions weighed in the previous HOQ. This HOQ is comprised of a pair-wise comparison between the design characteristics and functions necessary to support the RUINS mission.

Functions	Weights		Minimize Aerodynamic Impact	Engage Fixed Targets	Engage Moving Targets	Effectively Kill Targets	Minimize Collateral Damage	Minimize Weapon Complexity	Find and Fix Targets	
Detection of IED Activities	**0.136**	0.136							9	
Effective Engagement	**0.152**	0.152		9	9	9			9	
Timely Engagement	**0.152**	0.152	9	9	9	9				
Accurate Weapons	**0.152**	0.152				9	9			
Fix Target Location	**0.136**	0.136		9	9				9	
Minimize Impact to ISR Mission	**0.136**	0.136	9					9		
Minimize Availability Impact	**0.136**	0.136						9		
Check Sum	**1.000**	1.000								
Goal Value										
Threshold Value										
Weighted Performance			2.6	4.0	4.0	4.1	1.4	2.4	3.8	22.3
Percent Performance			0.116	0.178	0.178	0.185	0.062	0.110	0.171	1.000 Check

Design Characterisitics

Figure 15 - HOQ 3

The results of the third-level HOQ show that design characteristics that impact target engagement functionality are the highest weighed items. Minimization of UAV performance impacts follows target engagement characteristics. These results are brought forward to HOQ 4, shown in Figure 16, which determines actual physical items that are crucial for mission success.

Design Characteristics	Weights		Weapon Weight	Maximum Weapon Rounds at Takeoff	Maximum Weaponized UAV Range	UAV On-Station Time	Stand-off Range	Minimum Weapon Range	Maximum Weapon Range	Weapon Speed	Weapon Accuracy	Warhead 50% Pk Range Human (Radius)	Warhead 50% Pk Range Truck (Radius)	Actual Measurement Metric
			UAV Performance & Susceptibility					Weapon Delivery Performance						Impact on System
Forms			lbs	count	km	hours	km @ altitude	km @ altitude	km @ altitude	m/s	avg. miss distance (m)	m	m	
Minimize Aerodynamic Impact	**0.1165**	0.1165	**9**	**9**	**9**	**9**	**6**							
Engage Fixed Targets	**0.17801**	0.17801		**9**	**3**	**3**	**3**	**9**	**9**	**3**	**9**	**6**	**6**	
Engage Moving Targets	**0.17801**	0.17801		**9**	**3**	**3**	**3**	**9**	**9**	**6**	**9**	**9**	**9**	
Effectively Kill Targets	**0.18453**	0.18453		**9**			**3**	**9**	**9**	**9**	**9**	**6**	**6**	
Minimize Collateral Damage	**0.06151**	0.06151									**9**	**9**	**9**	
Minimize Weapon Complexity	**0.10997**	0.10997		**6**				**6**	**6**	**6**	**9**	**6**	**6**	
Find and Fix Targets	**0.17148**	0.17148			**9**	**9**	**3**	**9**	**9**					
Check Sum	**1**	1.00												
Goal Value														
Threshold Value														
Weighted Performance			1.0	6.6	3.7	3.7	2.8	7.1	7.1	3.9	6.4	5.0	5.0	52.2
Percent Performance			0.020	0.126	0.070	0.070	0.054	0.135	0.135	0.075	0.123	0.096	0.096	1.000 Check

Category Total = 0.340 Category Total = 0.468 Category Total = 0.191

Figure 16 - HOQ 4

HOQ 4 results indicate weapon effectiveness characteristics are the highest weighted items and essential to RUINS success. The QFD method is responsible for establishing the appropriate levels of design focus and the levels of risk if the RUINS requirements are not met. With HOQ 4, the team has identified that weapon speed, range, average miss distance, and warhead effectiveness are the top performance parameters that will impact RUINS the most. These weighted results will be used to calculate an overall-MOE (OMOE) of the RUINS.

1. Key Performance Parameters

The RUINS will support the deployment of the Coalition Forces throughout their military operations. These operations include the C-IED mission. To improve operations, certain capabilities need to be addressed: ability to accurately locate a target, ability to neutralize a target, while not detrimentally impacting the inherent UAV ISR capabilities. To verify these capabilities have been met, Key Performance Parameters (KPPs) and attributes translate capabilities into quantifiable characteristics that are testable.

KPPs are those characteristics that are considered essential to accomplishing the mission. After gaining stakeholder insight into what characteristics are high priorities to their individual

needs, research was conducted to help determine which parameters would result in mission failure or loss of target if not met. Two values for each parameter, threshold and objective, were identified. The threshold is the minimum acceptable value for the system. The objective is the desired value and is better than the threshold. The following are the key performance parameters or characteristics that are needed to satisfy the operational capability requirement that were decomposed from the customer desires and the Objectives Hierarchy via the QFD method.

a) UAV Performance & Susceptibility:

Weapon Weight was selected as a KPP because the UAV must be able to physically lift at least one weapon and associated launch/release equipment. The weight of the supporting launcher equipment is assumed to be equal to that of the weapon itself. The available Tier II payload dedicated to weapons is the maximum available payload. A single weapon and its associated launcher need to be 48 pounds or less. For scoring, the following formula was used:

Equation 1 - Scored Weapon Weight

Where:

Equation 2 - Weapon Weight Calculation

Number of Stowed Weapons at Take-off (number of rounds) was selected as a KPP because the UAV must be able to engage a target. The threshold value was set to one weapon. The objective would be to carry more weapons to allow engagement of other targets within the same sortie or reengaging the first target if the first weapon missed. For scoring, the following formula was used:

Equation 3 - Scored Number of Rounds

Where:

Equation 4 - Stowed Weapons at Take-off Calculation

Maximum Weaponized UAV Range was selected as a KPP because the UAV must be able to fly a certain round-trip distance in order to satisfy ISR and C-IED efforts. The team used the Shadow RQ-7 200's range as a representative performance estimate. This UAV has an estimated range of 109 km round-trip. The weaponized Tier II UAV must be able to fly with a 25 percent reduction in range, which equates to 80 kilometers. For scoring, the following formula was used:

Equation 5 - Scored Maximum Weaponized Range

RUINS UAV Endurance was selected as a KPP because it is the amount of time in hours that the RUINS system will be able to operate. The threshold values were based upon a percentage of the surrogate UAVs' endurance times listed in Table 10. The addition of an adjunct weapon system to any aircraft is not without its detrimental effects. For this, the team has proposed that a 25 percent reduction in endurance time is acceptable. The resulting threshold is 6

hours with an objective of 8 hours (original UAV endurance). For scoring, the following formula was used:

Equation 6 - Scored UAV Endurance

Where:

The AK-47 assault rifle represents an enemy stand-off capability of a maximum of 400 meters. This value was used to set the threshold for the Tier II weaponized UAV. The objective will be based upon visual detection by the unaided enemy eye at 500’ AGL. For scoring, the following formula was used:

Equation 7 - Scored UAV Stand-off Range

Where:

b) Weapon Delivery:

Minimum Weapon Range was selected as a RUINS KPP due to the Tier II engagement envelopes defined in Figure 25. The AK-47 assault rifle represents an enemy stand-off capability of a maximum of 400 meters. This value was used to set the threshold for the Tier I and Tier II weaponized UAVs. This weapon delivery parameter fits hand in glove with the

UAV performance impact/susceptibility parameter of Stand-Off Range. For scoring, the following formula was used:

Equation 8 - Scored Minimum Weapon Range

Where:

Weapon Maximum Effective Range was selected as a KPP as it takes into account 1m target and 3.5m target ID. The 1m target ID represents the objective of at least being able to launch at the 1m ID with EO sensors at 500' AGL. This KPP also takes into account the ability to effectively ID a 3.5m target via the onboard IR sensors. A threshold of 900 meters and an objective of 6500 meters were chosen. For scoring, the following formula was used:

Equation 9 - Scored Maximum Weapon Range

Where:

Weapon speed was selected as a KPP as it affects the amount of time the UAV may be susceptible to enemy defenses prior to weapon impact and the time the enemy has to react if

attacked. To allow consideration of all weapon types, a wide range of speeds was considered. A disposable armed UAV might have flight velocities as low as 20 knots. The threshold value for this KPP was selected as 10 m/sec, which approximately corresponds to 20 knots. An objective value was selected that reflects the approximate in-flight speed of some slower missile systems, 150 m/sec.

Equation 10 - Scored Weapon Speed

Where:

Equation 11 - Weapon Speed Calculation

Weapon Accuracy was selected as a KPP because of the concern over collateral damage when engaging targets in urban environments. The threshold and objective values were based on the target sizes that were used in the optical performance analysis. The threshold is to hit a 3.5 m x 3.5 m vehicular target and the objective is to hit a 1.0 m x 1.0 m target that is representative of a human. For scoring, the following formula will be used:

Equation 12 - Scored Miss Distance

Where:

Equation 13 - Miss Distance Calculation

c) Weapon Warhead Effectiveness:

A common metric of weapon effectiveness is the "probability of kill" (P_K). Better termed the "probability of damage," it is a statistical measure of the probability of an entity suffering damage sufficient to cause its contribution to the battle force to be removed. P_K in its strictest sense is a combination of several probabilities depending on the type of weapon, delivery, and target. For the purposes of the warhead effectiveness metrics in this study, P_K will be considered to be the probability of causing severe damage to a human target or damaging — causing mobility damage — to a vehicle target. The metric of interest selected is the 50 percent warhead lethality range. The range is defined as the range at which a target has a 50 percent probability of suffering a specific level of damage. The range is dependent upon the characteristics of both the warhead and the target and will be determined for each candidate weapon as part of the analysis. The measure was selected as a KPP for two reasons. First, the warhead must demonstrate adequate damage potential to cause the target to be removed from the battle at demonstrated miss distances for a particular weapon. If it does not contain this potential, the weapon must be considered ineffective. Second, the warhead should not cause excessive collateral damage. In any battle, some collateral damage is to be expected and cannot be avoided. However, these types of losses can have profound effects on the morale and support of the local populations. While the possibility of collateral damage is not a KPP, and so not considered in OMOE, some notion of its measure will be provided as part of the analysis of the candidate systems.

Equation 14 - Warhead 50% P_K Range (Human)

Where:

$P_{K|HIT(HUMAN)}$ *is defined as 0.7*

Equation 15 - Warhead 50% P_K Range (Vehicle)

Where:

$P_{K|HIT(VEHICLE)}$ *is defined as 0.5*

The resulting RUINS KPPs and their associated threshold and objective are represented in Table 13.

Table 13 - RUINS KPP Threshold and Objective Values

System Impact	TPM	Threshold	Objective
UAV Performance & Susceptibility			
	Weapon Weight (single weapon + launcher), lbs.	48	< 48
	Weapon Rounds at Takeoff, count	1	6
	Maximum Weaponized UAV Range, km	80	109
	UAV Endurance, hours	6	8
	Stand-off Range, m	400	4,000
Weapon Delivery			
	Minimum Weapon Range, m	400	4,000
	Maximum Effective Weapon Range, m	900	6,500
	Weapon Speed, m/s	10	150
Weapon Warhead Effectiveness			
	Weapon Accuracy, m	3	2
	Warhead 50% P_K for Human Target	4	3
	Warhead 50% P_K for Truck Target	4	3

2. Overall Measure of Effectiveness (OMOE)

The KPPs were used to determine an Overall Measure of Effectiveness (OMOE) for each candidate weapon integrated onto the surrogate UAV. Each KPP belongs to an OMOE impact category. The impact categories describe the effects that the KPP has on the entire RUINS system. The results of HOQ 4 translate to OMOE weights for the following:

Table 14 - OMOE Weights

OMOE Impact Category	Weight
UAV Performance & Susceptibility	0.340
Weapon Delivery	0.468
Weapon Warhead Effectiveness	0.192
OMOE Total	**1.000**

The team evaluated each candidate weapon integrated on the surrogate UAV via this weighting method. Total OMOE cannot exceed 1.00 and the higher the weight, the better. Scoring for each KPP was accomplished as follows:

- KPPs where higher values are better were assigned a calculated score of 0 to the lowest value (threshold) and a calculated score of 1 to the highest (objective) value. Values between the threshold and objective were scaled to form the calculated score. This calculated score was multiplied by the KPP computed weight to achieve an overall score for that KPP. If the attained value was less than the threshold, a calculated score of 0 was assigned. If the attained value was higher than the objective, a calculated score of 1 was assigned.
- KPPs where lower values are better were assigned a calculated score of 0 to the highest value (threshold) and a calculated score of 1 to the lowest (objective) value. Values between the threshold and objective were scaled to represent the calculated score. This calculated score was to be multiplied by the KPP computed weight to achieve an overall score for that KPP. If the attained value was more than the threshold, a calculated value of 0 was assigned. If the attained value was less than the objective, a calculated score of 1 was assigned.

The OMOE Impact Category weight results were considered in system analysis and final recommendation. Figure 17 is representative of the OMOE scoring chart. The final OMOE results are presented in Chapter 4 and include the performance results.

KPP Key	
	Computed weight
	Weight obtained from QFD 3

Effects of adding weapon on the UAV performance & Susceptibility					
KPP	**KPP Attribute Name**	**KPP Threshold**	**KPP Goal**	**Attained**	**Units**
0.020	**Weapon Weight Single Weapon + Launcher**	48	< 48		lbs
0.020	Calculated Score				
0.126	**Maximum Weapon Rounds at Takeoff**	1	6		count
0.126	Calculated Score				
0.070	**Maximum Weaponized UAV Range**	180	250		km
0.070	Calculated Score				
0.070	**UAV On-Station Time**	6	8		hours
0.070	Calculated Score				
0.054	**Stand-off Range**	400	4000		m @ 2000 ft. AGL
0.054	Calculated Score				
Weapon Warhead Performance					
KPP	**KPP Attribute Name**	**KPP Threshold**	**KPP Goal**	**Attained**	**Units**
0.135	**Minimum Weapon Range**	400	4000		m @ 500 ft. AGL
0.135	Calculated Score				
0.135	**Maximum Effective Weapon Range**	900	6500		m @ 2000 ft. AGL
0.135	Calculated Score				
0.075	**Weapon Speed**	10	150		m/s (avg of min & max flights)
0.075	Calculated Score				
0.123	**Weapon Accuracy**	3	2		avg. miss distance (m)
0.123	Calculated Score				
Weapon Warhead Performance					
KPP	**KPP Attribute Name**	**KPP Threshold**	**KPP Goal**	**Attained**	**Units**
0.096	**Warhead 50% Pk Range Human (Radius)**	4	3		m
0.096	Calculated Score				
0.096	**Warhead 50% Pk Range Truck (Radius)**	4	3		m
0.096	Calculated Score				

Figure 17 - OMOE Weighting

G. Functional Analysis

The functional analysis started by incorporating responses from stakeholders and research into UAS and weapon operations. Typical UAS operations were broken down into the following top level functions.

- Perform External Control
- Prepare and Launch
- Fly Mission

- Recover

The addition of weapons to the system required modifications to all of the top level functions. Modifications included adding functions for maintenance, pre-flight checks, and recovery of the weapon. Functions that described the targeting and launching of the weapon were also included.

1. Functional Hierarchy

The top level functions were decomposed to create the functional hierarchy. Further decomposition can be found in Appendix A.

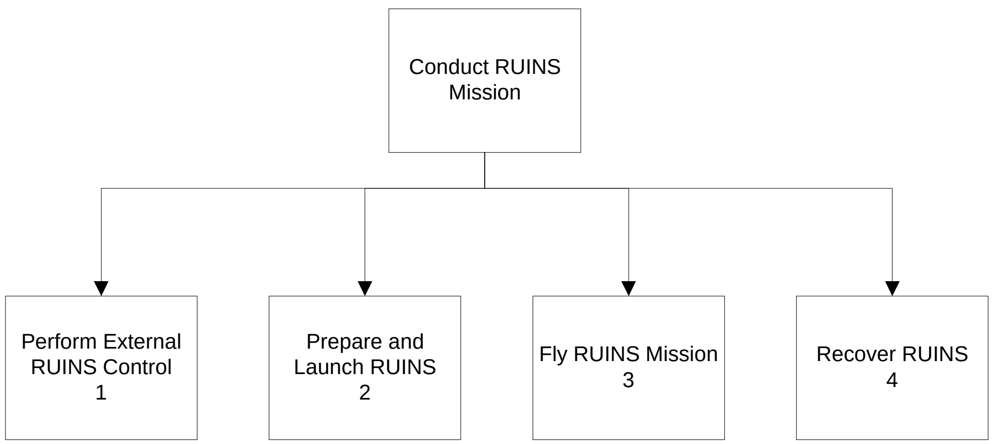


Figure 18 - RUINS Top Level Functional Hierarchy

a) Perform External RUINS Control

Control from the ground station was broken down into several sub-functions. Communication and control of the UAV would be largely similar to traditional ISR operations. The addition of weapons would require the data links and control hardware and/or software to be modified. At a minimum, the ground station would need to display weapon readiness to the operator, and have a method of remotely firing the weapon. The firing mechanism should be designed to avoid similarity with other controls to avoid accidental firing or confusion. The amount of training operators would require would depend on the automation of the software and the extent to which the new features are integrated into the hardware and software.

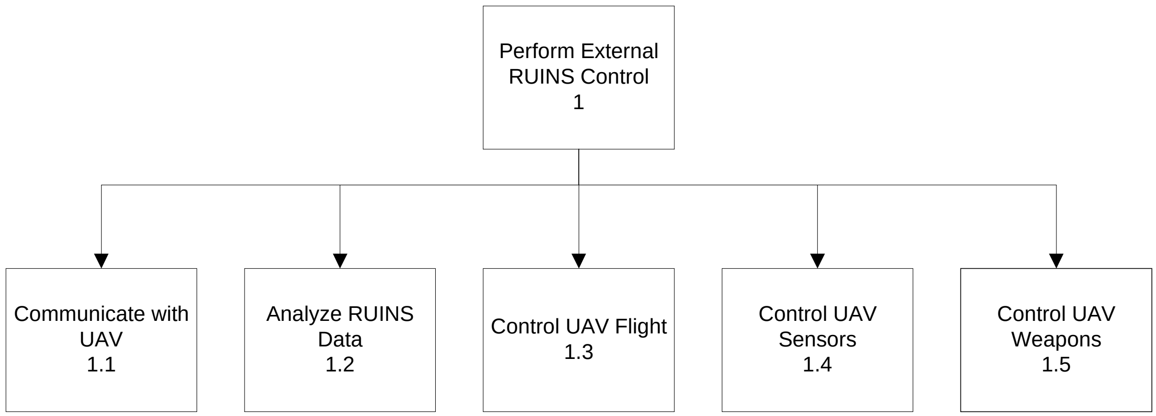


Figure 19 - Perform External RUINS Control Functional Hierarchy

b) Prepare and Launch RUINS

In addition to the standard UAS launch preparation functions, loading the appropriate payload onto the UAV was added. The other standard functions include programming and fueling the UAV, performing preflight checks, and loading the UAV onto the launcher. Loading weapons onto the UAV should be done at a neutral height to minimize strain on the loaders. Although the weapons are relatively light, loading onto the underside of a small UAV could be cumbersome. Raising the UAV on a working platform or stand would allow for easier access to the weapon attachment points. The launch system should be keyed so that the weapons can only be loaded in the correct orientation. Once the weapon is loaded, it is advised that the launcher/weapon produce a tactile indication that the weapon is fully and correctly engaged. Prior to UAV launch, any weapons domes, fiber optics, and electrical connector covers should be removed. Connections between the weapon and launch/release assemblies should be kept to a minimum. Electro/mechanical connections should be keyed to avoid incorrect installation.

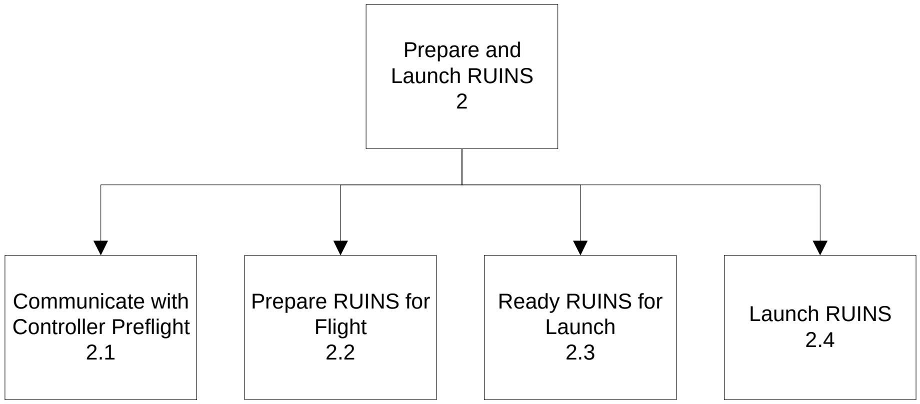


Figure 20 - Prepare and Launch RUINS Hierarchy

c) Fly RUINS Mission

The major functions of RUINS in flight would not change much from an ISR mission. The addition of weapons would add the Deliver Weapons function and require changes to the Communicate with Controller in Flight function. Delivering weapons would involve detecting and tracking targets. If a potential target was found, the UAV would need to maintain the target track. Ideally this would be automated and performed either by the UAV itself or by automated commands from the Ground Control Station. One possible method of accomplishing this would be to have a dynamically updated waypoint that the UAV would either orbit or make repeated passes over. The target tracking algorithms would update the waypoint to compensate for target movement. The weapon would be activated and queued to the target if the target was identified by the operators. The decision to release the weapon would be based on the current ROE.

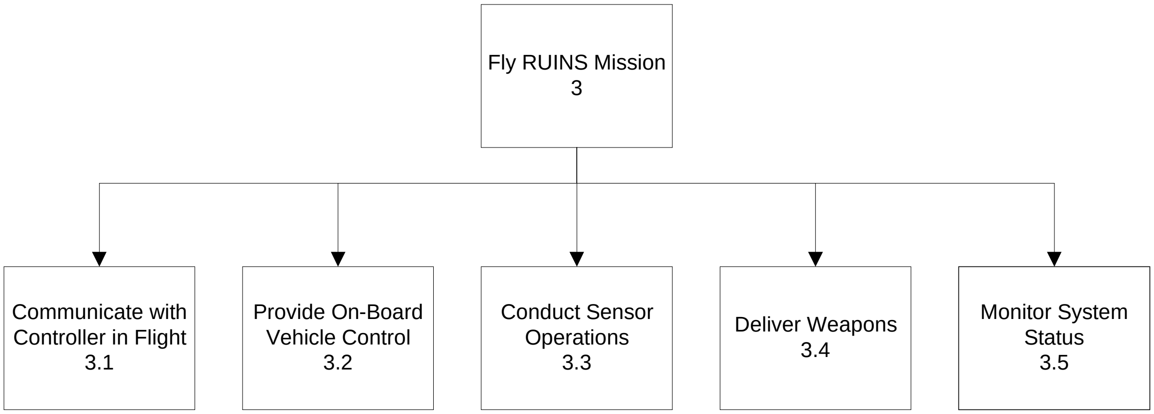


Figure 21 - Fly RUINS Mission Hierarchy

d) Recover RUINS

Recovering the UAV after a mission will require additional functions to safely deal with weapons. Some UAS incorporate a recovery device while others simply land in a cleared area. A recovery device would possibly need modifications to handle the increased weight and approach speed of a UAV returning with a weapon. Additionally, it would have to recover the UAV without damaging the weapon. If there was a hang fire during the mission, where the weapon was commanded to fire but did not leave the UAV, an attempt to jettison it prior to landing would need to be made. The ground control system would need to be altered either in hardware or software to add the jettison functionality. A recovered UAV with weapon aboard will need to be transported to an appropriate weapons removal site. It is possible that the recovery device would be collocated there to save time. The ordnance crew would need training similar to that of manned aircraft on proper handling procedures. Cross-training on manned systems could provide cost and manpower savings.

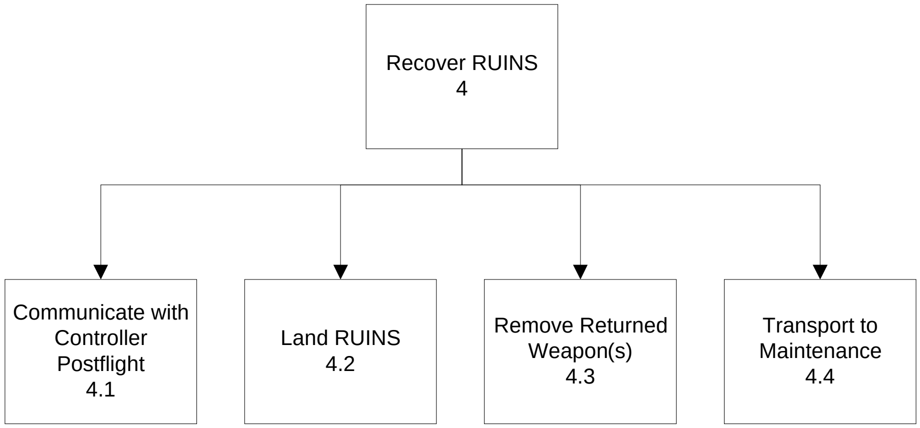


Figure 22 - Recover RUINS Hierarchy

2. Functional Flow Block Diagrams (FFBD)

Once the functions had been developed, the functional flow of the system was created. FFBDs depict how information travels between the various functions and sub-functions, as well as showing the temporal relationship between the functions. The order that functions are performed is not captured in the functional hierarchy. Detailed investigation can be found in Appendix B.

a) Perform External RUINS Control

Controlling RUINS occurs in parallel with the other top level functions as shown in Figure 23. The communication and control sub-functions also function in parallel with each other as shown in Figure 24. These all must be operating properly to successfully complete a mission.

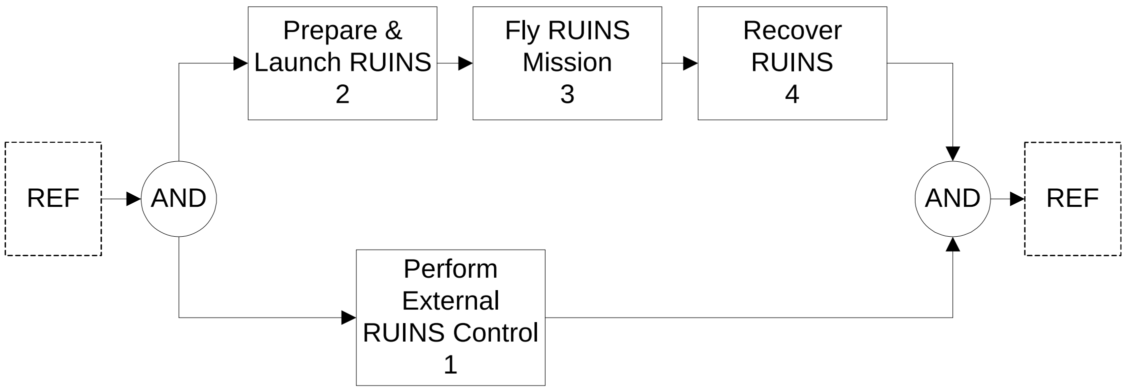


Figure 23 - RUINS Top Level FFBD

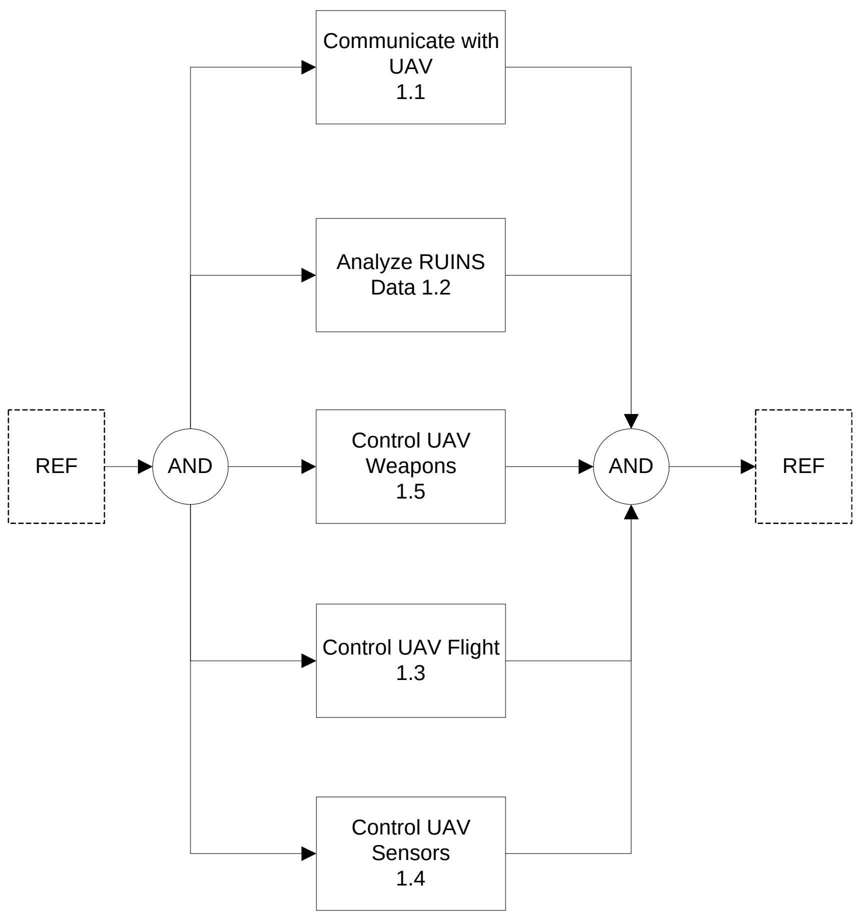


Figure 24 - Perform External RUINS Control FFBD

b) Prepare and Launch RUINS

Prior to launch, RUINS must be prepared for launch as shown in Figure 25. First communication with the controller must be established and mission information transmitted to the UAV. This would include either manually inputting weapon parameters or selecting a preset option. The UAV would then be prepared for flight by loading fuel and weapons. It would then be moved to the launch area, positioned for launch, and the weapons prepared or armed by ordnance crews. Prior to launch, the flight controls would be verified and the system energized. If all checks were successful, the UAV would be launched and climb to cruise altitude.

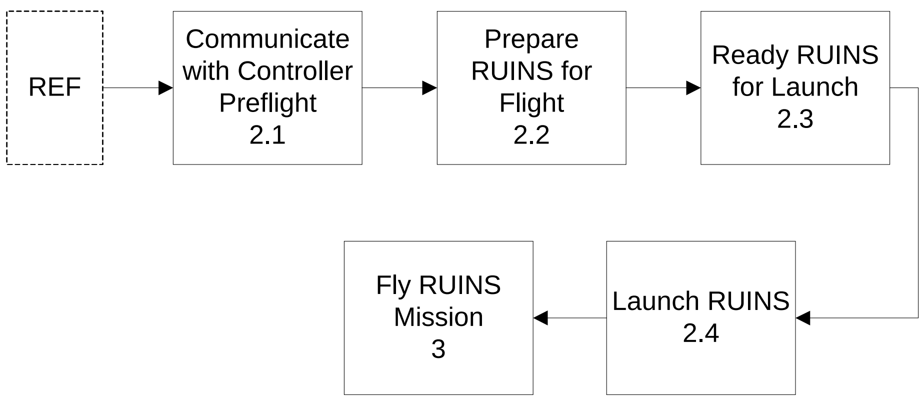


Figure 25 - Prepare and Launch RUINS FFBD

c) Fly RUINS Mission

Once the UAS had been launched, it would begin performing the mission. Several functions would be performed in parallel as shown in Figure 26. It would communicate with the ground controller. Commands would be uplinked while system status and sensor information would be downlinked. Once a target is found, the operator would designate it and manually release the weapon.

To properly employ the weapon, the ground control system should communicate relevant information to the operator such as weapon information and target location. The preloaded weapon information would allow the system to display the maximum effective range of the weapon. For most weapons, this would be a cone-shaped region in front of the UAV. This

indicator would be dynamically overlaid on the two-dimensional navigation map or possibly as a three-dimensional object overlaid on the sensor's video image. The three-dimensional object would require much more processing capability on the ground control system. Ideally, the range indicator would change shape to represent the actual capability of the weapon. If the UAV pitched down or decreased altitude, this could decrease the range of the weapon and the indicator would shorten. Once in range and properly oriented with respect to the target, the display would notify the operator to release the weapon. This could be accomplished by changing the color of the range cone, displaying a text message, making a distinctive noise, or some combination of those alerts. Additionally, the display should indicate the number of weapons available, weapon status, and safe-arm condition.

To ease the workload on the operator, the target should be automatically tracked as much as possible, once designated. Keeping the sensor centered on the target, or the correct position of the target on the navigation display, would free the operator to verify the identity of the target and obtain proper authorization to engage with a weapon. Having to manually keep the target in sight while maneuvering the UAV into position, and then firing the weapon precisely on target, could be very difficult to accomplish. This difficulty is increased by the quality of the video being sent from the sensor or weapon. The display should also keep a box or icon over the target to aid in distinguishing it from the background.

Passing the target location to the weapon should also be automatic. The UAV would be calculating the target's position and converting it to location coordinates. These coordinates should be passed to the weapon through a machine-to-machine interface to avoid human error. The display should show the coordinates given to the weapon so the operator can verify them. If a weapon is guided optically, the image of the target should be transferred to the weapon similarly, or the weapon's sensor imagery should be viewable on the ground control system. With the weapon properly queued from the UAV sensor, the operator should only have to verify that it is correctly targeted.

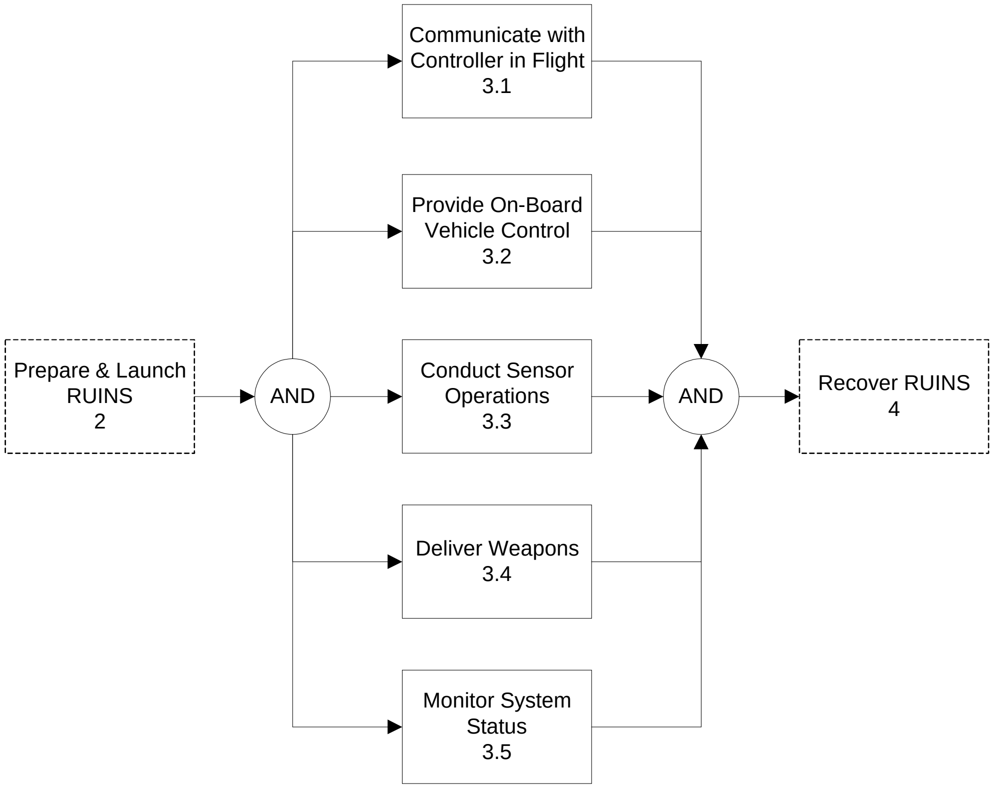


Figure 26 - Fly RUINS FFBD

d) Recover RUINS

After completing the RUINS mission, the weapon would need to be recovered. Communication with the controller would be performed in parallel with the landing and disarming functions as shown in Figure 27. Landing would involve commanding any returning weapons to be safe. In the case of a hung weapon, it would be jettisoned if possible. Jettisoning the weapon would require the addition of a jettison command in the ground control system. The UAV would then be landed or recovered and de-energized. Ordnance personnel would remove the weapons and then transport the UAV to a safe location. Once removed, the weapons would be placed in an appropriate storage location. The UAV would then be moved to the maintenance area to be readied for its next mission.

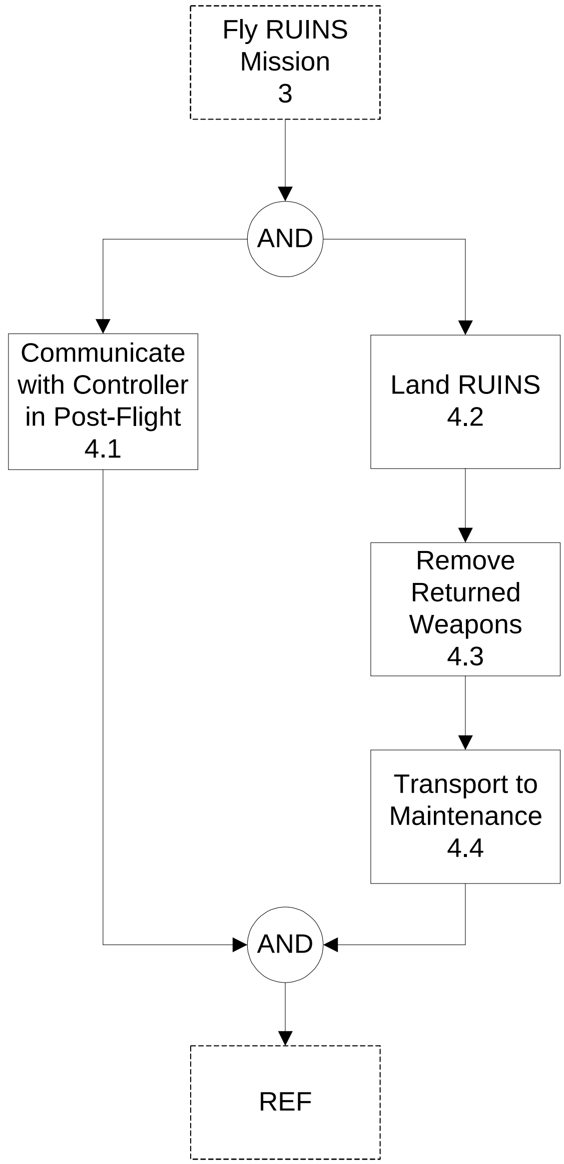


Figure 27 - Recover RUINS FFBD

H. Architecture

Weaponizing Tier II UAVs is becoming a desirable concept for the future warfighter. UAV weaponization examples and endeavors are few and far between. The best weaponization examples would have to be taken from manned aircraft. The RUINS system architecture was mapped to the IDEF0 system context and is shown in Figure 28. The architecture is defined by the functions in Conduct RUINS Mission A-1. Each component's functionality is defined from the

functional flow block diagrams. Further breakdown can be found in Appendix C. Although UAV weaponization impacts the entire system, consideration should focus highly on the weapon integration effort.

The RUINS Weapons Management Controller and RUINS Payload Ground Controller is a hardware/software combination that specifically addresses the various platform/weapon combinations in a flexible concept. This will make platform/weapon combinations possible without costly integration for each variant. The RUINS UAVs will have limited payload capability and thus the corresponding weapons will require development of the launchers, pylons, and data links to integrate the entire package. The Weapons Management Controller and Payload Ground Controller will be at the top of this integration effort.

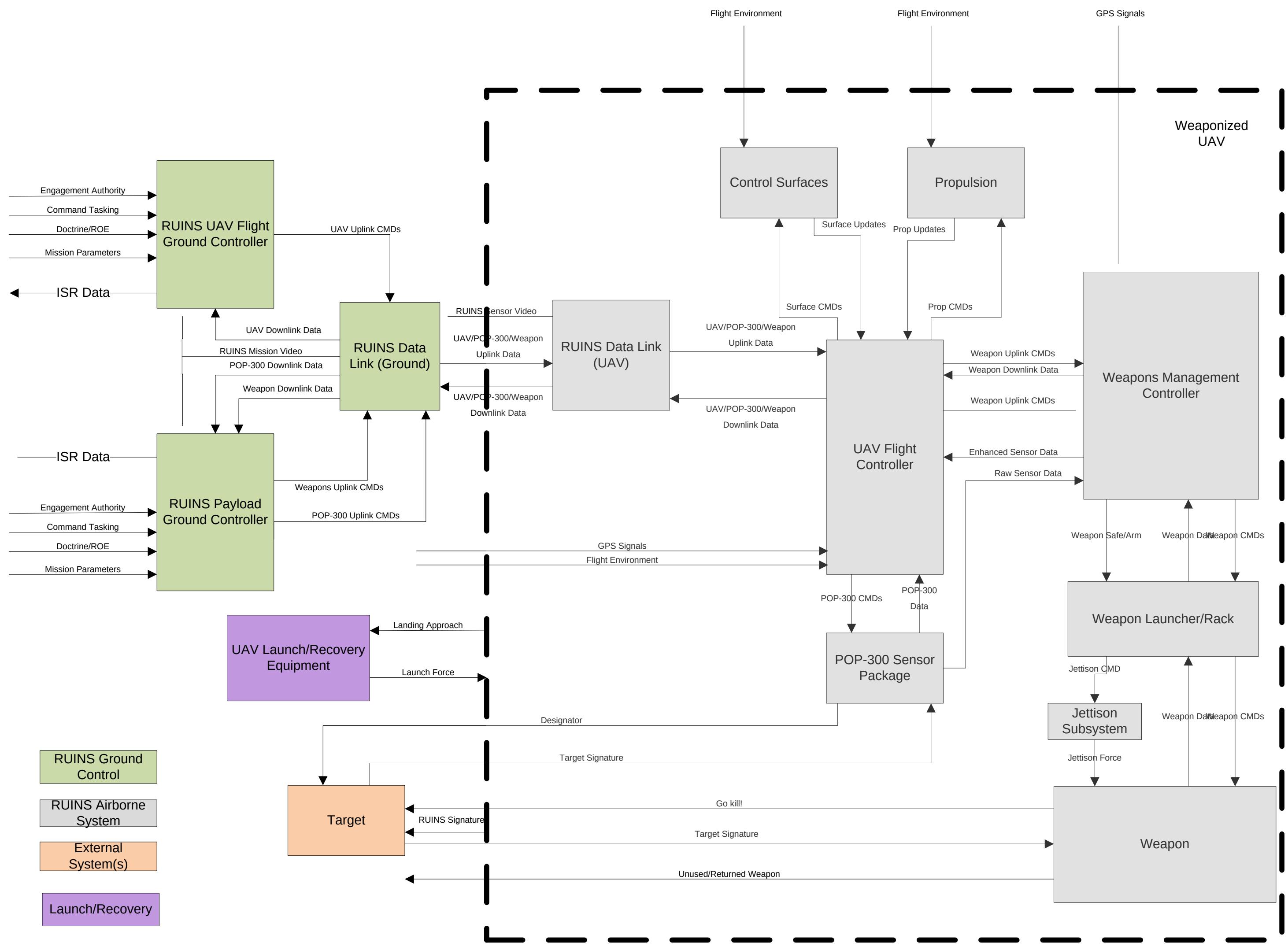


Figure 28 - RUINS Architecture

The RUINS architecture is designed to control weapons from the UAV platform. This is accomplished through “basic” commands from the ground control station to the UAV’s avionics, managed through the Weapons Management System (WMS), and submitted to the specific weapon mounted to the vehicle. Each weapon has a specific sequence of events it must go through before launching the weapon to target. These weapon specific data requirements are expected to be different for each weapon and would be configured into the weapons management controller. The weapon must be within the vehicle operational limitations in order to take-off and deliver the weapon to a specific target.

For the small UAVs whose traditional role was as an ISR platform, ground control station operations had both a vehicle controller and a payload operator. The UAV generally consisted of a sensor package that included multiple sensors integrated into the UAV airframe. The UAV’s mission was to gather data and send it back to the payload operator for further analysis and dissemination to appropriate command levels. The operational system consisted of a UAV/sensor and a ground control station split into a payload operator and vehicle operator displays. The system had no software to provide human interaction with a weapon on the UAV. Integration efforts within the system software should include the opening a “new screen” on either vehicle or payload displays.

I. Summary

The Problem Definition phase of the project focused on further definition and refinement of the directions to be taken as the project proceeds. Stakeholders were engaged to obtain their inputs into possible uses and limitations of the system, resulting in a set of representative mission scenarios for use in later modeling efforts. From these interactions, initial requirements were developed, and an objectives hierarchy with related measures of effectiveness created. This allowed the allocation of objectives, using Quality Functional Deployment methods, from objectives to physical instantiations. Measures of performance, key performance parameters, and an overall measure of effectiveness were developed for later use in the evaluation of alternatives. Using the identified functional allocation, an architecture for the project was defined. The project then proceeded to the identification of possible options in the Design and Analysis phase.

III. DESIGN AND ANALYSIS

The examination of sponsor needs and requirements documented in the previous chapter narrowed the scope of the problem. Representative scenarios were developed that detail the anticipated use of the system, allowing a determination of tasks to be accomplished, and helped define the system boundary. Operational objectives and key performance parameters were developed, which will allow future evaluation of the feasibility of proposed alternatives as they are developed.

Prior to developing alternative solutions to the identified problem, further analysis was performed. During this phase, the proposed use of the system was closely examined to understand the sequence of operations that must be performed during a weapon engagement. As the RUINS concept was intended to make use of minimally modified UAVs if possible, understanding of the existing capabilities installed was necessary. The anticipated enemy defenses were examined to identify possible areas of RUINS susceptibilities during a weapon engagement to assist in developing desired engagement ranges. At the same time, open source research was performed to identify possible candidate weapons that might be of use with the RUINS. Finally, an initial screening of the identified candidates was performed and a subset selected for further examination in modeling. Concurrently, a risk analysis was performed to identify risks associated with both the proposed alternatives and the processes used during the project. The output of the phase was a reduced set of candidate weapons and associated risks intended for further investigation in the following modeling stage.

A. Mission Cycle

For the scenarios explored in this research paper to provide useful insight, there were several factors that had to be understood. The following sections detail determining mission success, targeting accuracy, identification by a target, and weapon delivery accuracy.

1. Probability of Mission Success

Many metrics were proposed for the evaluation of the weapons' selected solutions. Many of the proposed metrics relied on knowledge of weapon specifics, which were not

initially known as weapons and had not been selected at the time. Instead, some concepts from weaponeering were used for early evaluations and to further define the problem. Weaponeering is defined as, "…the process of determining the quantity of a specific type of weapon required to achieve a specific level of target damage, considering target vulnerability, weapon effects, munition delivery errors, damage criteria, probability of kill, weapon reliability, etc." (Driels 2004). A rough evaluation of Probability of Mission Success (P_S) provided rapid insight into major issues with possible weapon systems and allowed rapid reduction to the most likely candidates. P_S has been defined by Morris Driels, a weaponeering instructor at NPS, as a combination of other probabilities that result from various aspects of the performance of the weapon, performance of the dispensing, vehicle vulnerabilities of the target, and effects of the environment. The general formula for P_S is given as

Equation 16 - Probability of Mission Success from (Driels 2004)

Where P_L is the probability of weapon launch
SSPD is the single sortie probability of damage.

A full assessment of P_S would provide the most complete evaluation of UAV-weapon-target performance. *SSPD* is defined as, "the probability that a single weapon will inflict on the target the amount of damage represented by the damage function. A sortie is a single pass by one aircraft over the target where one or more weapons can be released. For unguided weapons only one weapon was released…For guided weapons however, more than one weapon can be released [with an appropriate time delay] against a single desired mean point of impact" (Driels 2004). However, determination of *SSPD* would prove difficult at this time as little definite was known concerning the possible weapons. A full calculation of *SSPD* would require in-depth knowledge of the weapon warhead characteristics, target vulnerabilities, and weapon delivery geometries. Instead, some measures of relative system performances were

derived from the piecewise evaluation of the systems and probabilities that contribute to P_S determination (Driels 2004).

2. Target Engagement Sequence

P_S is an overall measurement of the results of the targeting cycle. Targeting is where mission objectives are turned into plans for actions against targets. The targeting cycle may be either deliberate or dynamic. In both, the focus is on achieving the commander's objectives. Targeting is performed for both kinetic and non-kinetic actions. Deliberate targeting is "…the procedure for prosecuting targets that are detected, identified, and developed in sufficient time to schedule actions against them in tasking cycle products." In comparison, dynamic targeting is all targeting that occurs outside of deliberate targeting (AFDD 2.19 2006).

Entry into the targeting cycle is at the "Find" stage. During this stage, a search is performed for possible targets that have been identified and evaluated prior to the mission. Once a possible target is identified, it is further classified into probable time-sensitive target, time-insensitive target, unknown classification, or not a target.

If classified a target and deemed "worthy of engagement," the "Fix" stage determines the target position and other information with sufficient definition to allow engagement. Once the target is fixed, the track stage "takes a confirmed target and its location, maintains a track on it, and confirms the desired effect against it." If target track is lost during this stage it may be necessary to repeat both the "find" and "fix" stages. This stage, by constantly tracking the target, maintains target identification.

The "target" stage verifies the identified target engagement and obtains necessary approvals to perform the engagement. During this stage, possible engagement options are considered. Approvals for engagement depend on several factors, including location of weapon assets, ROE, target range, accuracy of targeting information, and weather. This stage is often the most time consuming of all the stages, but may be accomplished in parallel with earlier stages.

In the "engage" stage, the weapon operator is ordered to engage the target by the engagement authority. The desired outcome of the stage is a "successful action against the target."

Following the "engage" stage, the "assess" stage evaluates desired results against the target with the results observed. In the case of a time-sensitive target, rapid assessment is often desired. Depending on the results of the assess stage, the cycle may return to the "target" stage and again engage the target if the weapon system has capabilities remaining (AFDD 2.19 2006).

3. Onboard Sensors and the Probability of Launch

The probability of launch (P_L) is defined as "the probability that the weapon was launched based on the target being detected." (Driels 2004). For an air-delivered weapon, it is the probability that the weapon was successfully dispensed, ejected, or deployed by the carrying aircraft.

P_L reflects the success that the aircraft has in detecting, classifying, and tracking a target to the level of certainty required by the engagement authority as well as other external conditions, such as weather. Further analysis of the onboard optical sensor system was performed to understand its impact to the targeting cycle and engagement.

The man-in-the-loop in a UAV system is located external to the air vehicle itself. As a result, no human eyes are directly observing the target scene from the location of the UAV. Instead, imaging systems in both visible and infrared (IR) spectral bands are used to provide situational awareness to the UAV operator on the ground. The imaging systems may have varying levels of resolution and tracking capabilities that make timely, positive target classification and verification difficult. The spectral bands available may not be optimum for the imaging task at hand.

Typically UAVs are equipped with optical systems that operate in one or multiple spectral bands defined as follows: visible (0.4 – 0.8μm), mid-IR (3 – 5μm), and long-IR (8 – 12μm). In all of these cases, the optical systems are passive. Though some of the man-portable UAVs offer an IR laser pointer, they are not intended for onboard imager

illumination and typically operate near the 0.85μm band, and so are outside of the peak response area of the IR imagers.

Two types of radiation are available for use by the passive optic sensors: emitted and reflected. Radiation frequency emissions can be modeled by a blackbody radiator. It is found from these devices that as temperature increases, emitted wavelength decreases. Figure 29 illustrates the emitted frequencies of a blackbody at 6000 Kelvin, which is approximately the temperature of the surface of the sun. This figure, while representing what frequencies the sun emits, does not represent the frequencies that actually reach the Earth's surface, as there is attenuation and filtering due to the atmosphere. The natural visible light observed on Earth is due primarily to the emissions of the sun and stars. Other natural sources of light are also of high temperature, such as fire. When an object is observed under natural illumination, it is generally due to the reflection of the light produced by the sun. At night, a reduced amount of visible light is available from either the moon's reflection of the sun or starlight. Standard visual cameras make use of the radiation wavelengths in this band.

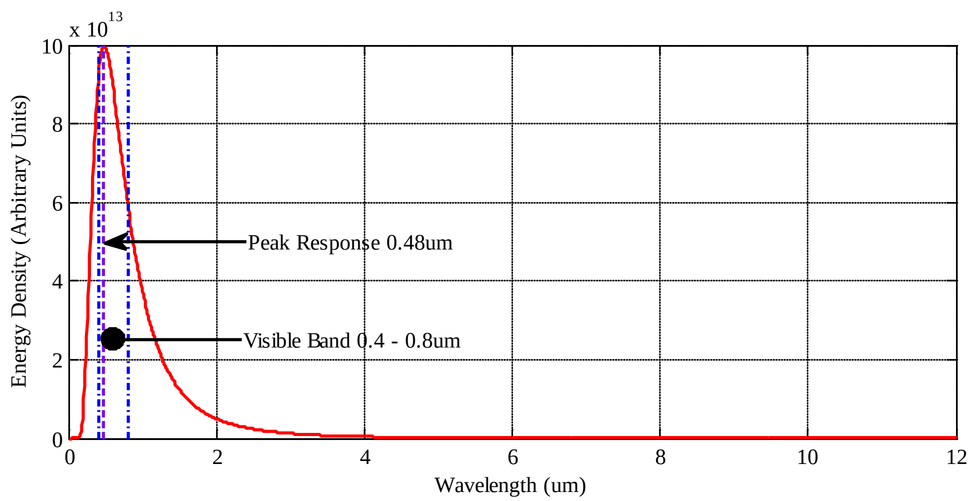


Figure 29 - 6000 Kelvin Blackbody Curve

In contrast, IR imagers receive and translate energy of wavelengths beyond the visual bands. Sources of IR energy can again be reflected from other sources. However, there are many systems that emit directly in the IR bands. Consider a human body with its

mean operating temperature of 98.6°, or 310 Kelvin. As shown in Figure 30, peak frequency is approximately 9.4μm, near the middle of the long-wave IR band. This radiation is available for detection both day and night. As the blackbody temperature increases, the peak wavelength of the emitted radiation shifts to shorter wavelengths.

Both types of UAV have provisions to take advantage of the passive IR emissions. The man-portable UAV IR imaging system operates in the 8–12μm. The imaging micro bolometer technology used operates at ambient temperatures and requires no detector cooling, reducing power requirements and weight. However, the technology is not as sensitive to temperature differences and the payload limitations restrict the optics that may be carried. In comparison, the tactical UAV has the option of a 3–5μm imager system. Its Indium Antimonide (InSb) detector array is cooled to approximately 77 Kelvin using either liquid nitrogen or closed-cycle cooling to reduce detector noise and increase sensitivity, allowing detection of slight temperature differences. The increased payload of the tactical UAV allows for much improved optics to be used, greatly increasing the capabilities of both the visible and IR imagers.

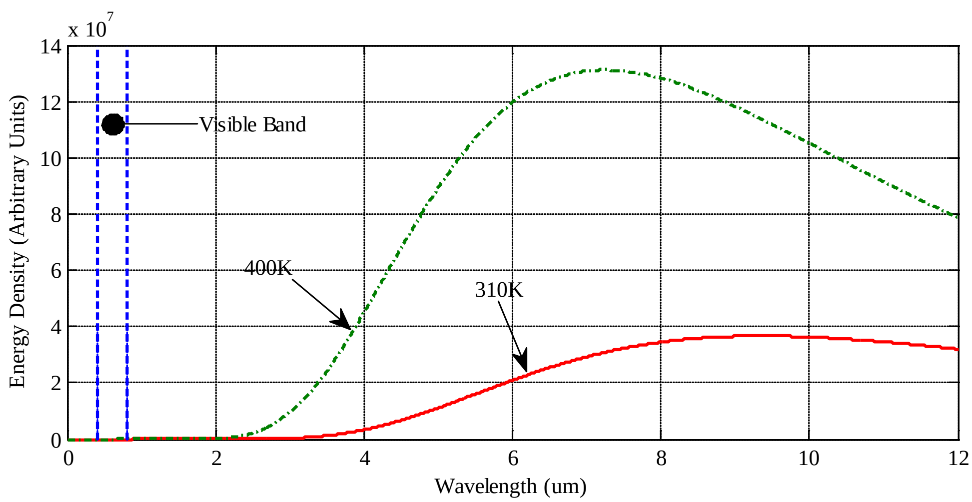


Figure 30 - 310 Kelvin and 400 Kelvin Blackbody Curves

Table 15 shows the specifications used to simulate the surrogate optical systems. The parameters used in these specifications are estimates based on available information and engineering judgment.

Table 15 - Surrogate UAV Optical Specifications

Surrogate UAV Optical System Specifications				
UAV Type	Spectral Band (µm)	Array Size	Pixel Dimensions (µm)	Field of View
Man-Portable	8–12	320x240	51	5°
	0.4–0.8	768x494	10	5°
Tactical	3–5	640x480	25	7° (wide) 1° (narrow) Continuous zoom
	0.4–0.8	768x494	10	29° (wide) 9.2° (medium) 2.3° (narrow)

The optical information transmitted from the UAV will ultimately be used to make the final engagement decision by operators on the ground. However, the information received is of varying quality depending on the range to the possible target. The information necessary for determination of a possible target does not necessarily rise to the same level as that needed to make a lethal weapon engagement decision. Visual target acquisition steps and their associated actions have been developed and are presented in Table 16.

Table 16 - Visual Target Acquisition Tasks (Driels 2004)

Task	Definition	Example Operator Action
Detection	Observer decides that an object in his field of view should be inspected further (e.g., a man-made object). It may have been visible before but was not distinguishable from other nearby objects.	Observer inspects the object, and takes actions to investigate further (e.g., turns the aircraft).
Recognition	Observer decides that the object belongs to a certain class of objects (e.g., vehicles). The level of detail required for recognitions depends on the operational situation and pre-brief.	Observer begins attack mode. The attack mode can include designation of the target to the fire control system, flying aircraft as required, etc.
Identification	Observer decides the object is in a particular subclass within the class (e.g., tank).	Observer continues attack and proceeds with weapon launch or release.

Determination of the information necessary to transition from one task to the next has been of interest to the military for years. John Johnson performed a study concerning these criteria for the Army in 1958, the results of which are still widely accepted. Johnson defined five levels of detection activity that are similar to those above: no detection, detection, shape orientation, shape recognition, and detail recognition (Johnson 1958). Johnson found that complex military targets could be represented by a transformation into lines of alternating high and low contrast as shown in Figure 31.

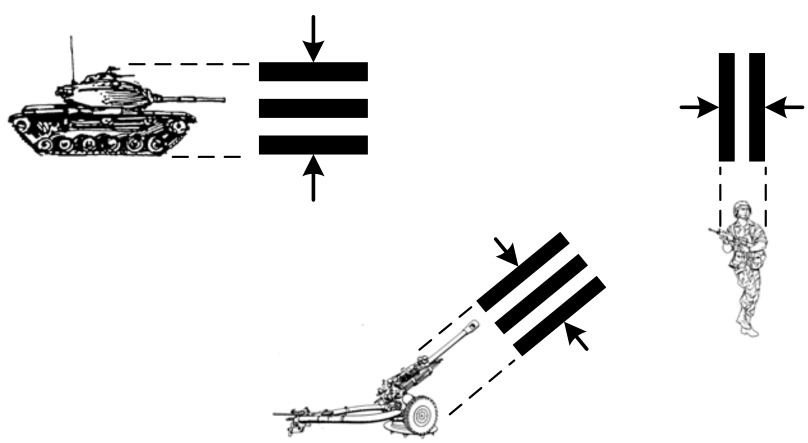


Figure 31 - Method of Optical Transformation from (Johnson 1958)

The “transformations were found to be independent of contrast and scene signal-to-noise ratio as long as the contrast in the resolution chart was the same as the contrast in the complex target” (Johnson 1958). Since then, a measure of spatial frequencies in cycles per angle subtended has been used as one measure in the evaluation of imager performance. Johnson compiled a table indicating the number of line pairs needed to accomplish various levels of detection. A portion of this table is presented in Table 17.

Table 17 - Optical Image Transformations after (Johnson 1958)

Target	Resolution per Minimum Dimension			
Broadside View	Detection	Orientation	Recognition	Identification
Truck	0.90	1.25	4.5	8.0
M-48 Tank	0.75	1.2	3.5	7.0
Jeep	1.2	1.5	4.5	5.5
Command Car	1.2	1.5	4.3	5.5
Soldier (standing)	1.5	1.8	3.8	8.0
Howitzer	1.0	1.5	4.8	6.0
Study Average	1.0 ± 0.25	1.4 ± 0.35	4.0 ± 0.8	6.4 ± 1.5

Johnson’s study went into much more detail concerning the contrast of the target in relation to the background. For the purposes of this study, his work with spatial frequencies was utilized to evaluate the identification threshold necessary to obtain authority to engage a target with a lethal weapon. In this study, the threshold of seven lines per angle subtended must be met to obtain engagement authority. By Nyquist discrete sampling criteria, greater than two samples per signal cycle period must be obtained to be able to accurately reproduce the frequency of the sampled signal. For the spacing of target-representative resolution lines, viewed at the detector, to be equal to the detector element spacing, the necessary target-to-sensor range that was calculated. At this range, the information present on the detector was just enough to properly classify the target per the seven lines per angle criteria. This calculated range formed the estimated “engage authority” range.

Spacing of the detector elements is critical in making these calculations. Consider the optically transformed gun target from Figure 31. If the transformation lines were horizontally aligned, as shown in the left drawing of Figure 32, the required spacing between detectors is of one measurement. However, if the transformation lines are oriented as shown in the right drawing, the effective necessary spacing is different. The worst case scenario would be when the target was oriented 45° to the detector array. In this situation, the minimum required detector spacing necessary for correct sampling criteria would be √2 x Detector Pitch.

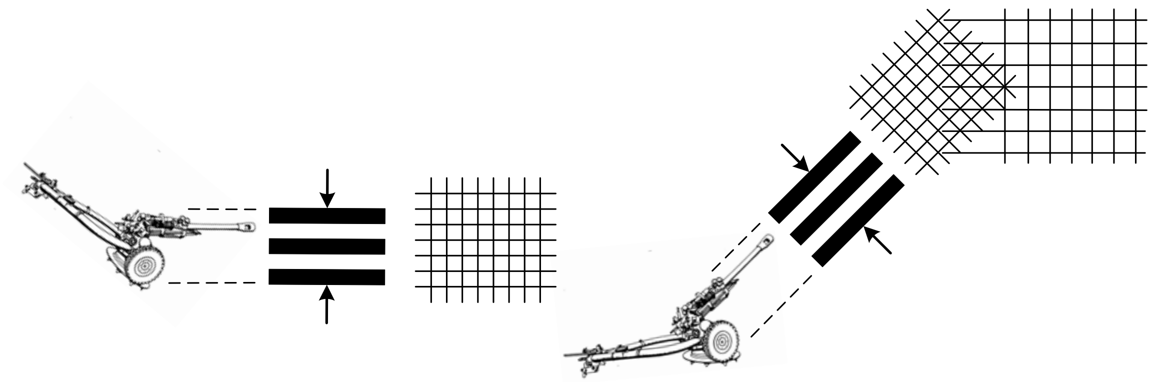


Figure 32 - Target Orientation and Pixel Spacing from (Johnson 1958)

A simple technique may be used to generate rough engagement range estimates. The effects of atmosphere were ignored in the calculations as the purpose is to determine the maximum range the surrogate UAV system might be able to satisfy engagement authority criteria. It is also assumed that the optics axis is orthogonal to the target. Estimated Field of View (FOV) and maximum number of detector cells across the FOV are known from Equation 17. It is assumed that the width of the FOV exactly fill the entire number of detector cells across the width of the detector array. Determination of the included angle, or angular subtense, captured by each detector cell in the FOV, may then be calculated by dividing the angular FOV by the number of detector cells across the FOV. To accommodate the possible orientation issue presented above, the angular subtense of each detector cell will then be multiplied by √2. The angle required to satisfy the Johnson criteria may then be calculated by simply multiplying the calculated angular subtense by two times the number of required cycles. Once this angle is known, the range may be

approximated by dividing the target height (or width) by the total Johnson criteria angle (in radians).

Equation 17 - Johnson Criteria Angle

Three resolution criteria were examined: detection (1 cycle), recognition (4 cycles), and identification (7 cycles). The estimated detector resolution limited criteria ranges were developed for two types of targets: a 3.5 meter square target, suggested as being similar to a vehicle, and a 1 meter wide target, representative of the width of a standing human with a weapon. The calculations assume perfect optics, and ignore the attenuation of target signature due to range or atmospheric diffusion. The results of these calculations are presented in Table 18 and Table 19.

Table 18 - Surrogate UAV Optical Performance (3.5m Target)

Surrogate UAV Optical Performance, 3.5m Wide Target					
UAV Type	Spectral Band (μm)	mrad/cycle	Detection (m)	Recognition (m)	Identification (m)
Man-Portable	8 - 12	0.7712	4,536	1,134	648
	0.4 - 0.8	0.3213	10,890	2,723	1,556
Tactical	3 - 5	0.0771	45,412	11,353	6,487
	0.4 - 0.8	0.1478	23,683	5,920	3,383

Table 19 - Surrogate UAV Optical Performance (1.0m Target)

Surrogate UAV Optical Performance, 1.0m Wide Target					
UAV Type	Spectral Band (μm)	mrad/cycle	Detection (m)	Recognition (m)	Identification (m)
Man-Portable	8 - 12	0.7712	1,296	324	185
	0.4 - 0.8	0.3213	3,111	778	444
Tactical	3 - 5	0.0771	12,970	3,243	1,853
	0.4 - 0.8	0.1478	6,767	1,692	967

In order to obtain weapon firing authority using the current surrogate UAV optical sensor systems, the analysis indicated the UAVs were required to be reasonably close in range to optically detect a target at the necessary resolution. The derived identification ranges were later used in developing an overall model of a possible target engagement. An analysis was needed to determine the detectability of the surrogate UAV. This allowed a better understanding of the feasibility of using a smaller, weaponized UAV in the C-IED mission.

B. Enemy Defenses and UAV Susceptibility Ranges

It was assumed that if the enemy were aware of impending attack it would react by either defending itself or fleeing. Consideration was made for both possibilities. The UAVs currently have many duties in addition to the attack/defense roles being proposed. The Tier I and II UAVs are constructed to maximize the available on-station time while performing their current ISR functions. As a result, the UAVs in these Tiers are equipped with little or no redundant capabilities and are constructed of light-weight materials. A single small caliber bullet has the capability of permanently disabling the aircraft. However, if the enemy does not realize an attack is imminent, the risk of damage to the UAV decreases and likelihood of weapon success increases. An examination of anticipated enemy defenses and ranges of UAV detection by the enemy was performed. Results of the examinations were used for further analysis of a possible target engagement.

1. Anticipated Enemy Defenses

The enemy, anticipated to be insurgents, was expected to have limited defense weaponry. What weapons they possess would be older and limited in capabilities. The weapons likely would have come from government magazines and armories. For example, the sudden defeat of the Iraqi armed forces resulted in weapon magazines unprotected and open to pilferage. Insurgents, while dedicated and competent, were not expected to be properly trained on the weapons they possessed. As a result, though optimum engagement conditions were considered, the results presented would likely be "worst case."

a) Man-portable Air Defense Systems (MANPADS)

MANPADS surface-to-air IR missiles were a significant threat to Coalition aircraft during the operations in Iraq. Many Coalition aircraft, primarily rotary wing, were lost to these types of weapons. Representative systems of this type include the NATO designators SA-7b "GRAIL" and SA-16 "GIMLET," both originally designed by the Former Soviet Union (FSU).

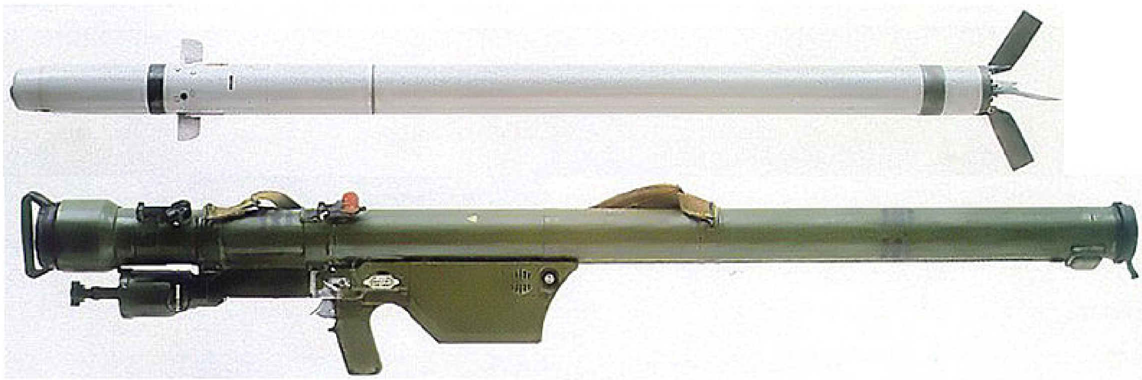


Figure 33 - Example IR MANPADS (Pakistan Defence 2008)

These types of weapons are capable of engaging targets at ranges of up to several nautical miles and altitudes of over 10,000' AGL. These rockets, once successfully launched, guide to intercept at ranges of up to several nautical miles and altitudes of over 10,000' AGL, reaching speeds approaching Mach 2. No operator intervention is required once launched, hence the term "fire and forget." Impact is required to trigger the warhead. Times required for missile launch are typically under 10 seconds once a target is detected (SA-7 GRAIL 1999).

While these types of weapons are definitely a threat to larger aircraft, the threat to the Tier I and II UAVs was considered to be minimal. These types of weapons rely on the IR self-emissions of a target to acquire and track to intercept. While a target's IR signature includes components related to reflected energy from either the sun or earth, the primary contributors are hot engine parts, engine exhaust, and heat resulting from air friction. These components are minimal for the Tier I and II UAVs. The airspeeds of the vehicles are low enough to cause little aerodynamic heating. The Tier I UAV has electrically powered propulsion, minimizing motor heating and eliminating exhaust,

though there are emissions due to the chemical actions of the battery. The Tier II UAV is powered by a small, well shielded internal combustion engine that provides for minimal exhaust and hot parts exposure. The SA-7b, originally fielded in the 1960s, was designed to engage unsuppressed jet engines. The IR signature from such a source is many orders of magnitude higher than that of the Tier I and II UAVs. The SA-16, while an improvement on the SA-7b due to better maneuverability and detection capabilities, would also likely encounter difficulty engaging the smaller UAVs due to the small IR signature.

b) RPG-7 Grenade Launcher

The RPG-7 is a front-loading, reloadable, recoilless, shoulder-fired antitank grenade launcher. Several different types of grenades are available for use with the weapon. The propulsion of the grenades consists of two portions. An eject motor propels the grenade from the launcher to a safe distance in front of the gunner. Stabilization fins that cause grenade rotation in flight deploy as the grenade exits the launcher. At a range of approximately 11 meters, the main rocket motor fires rapidly, accelerating the grenade to a maximum speed of 300 m/sec. If the grenade fails to impact a target after five seconds at an approximate range of 900 meters, the grenade will self-destruct. (U.S. Army Training and Doctrine Command 1976).

Figure 34 - RPG-7 40mm Launcher with Round (Pakistan Defence 2009)

Though the RPG-7 was originally developed as an anti-tank weapon, more recently it has been heavily used by insurgents. Several rotary-wing aircraft have been disabled due to grenades. While it may be relatively easy to employ the RPG-7 system, its effective use requires training and practice. Though the weapon is reasonably accurate, even well-trained gunners often incorrectly estimate ranges leading to a first round miss. Probability of a first round hit of a stationary M60 tank target at a range of 300 meters is less than 30 percent. If there is any wind present, the probability decreases, due to the large cross-sectional area of the projectile. Adding movement to the target also decreases probability of hit as the rounds are non-guided. However, due to the wide proliferation of the weapon and its ammunition, possible use against UAV targets cannot be discounted (U.S. Army Training and Doctrine Command 1976).

c) AK-47 Assault Rifle

The AK-47 is probably one of the best known rifles in the world. Originally entering service in 1947, the FSU design has demonstrated itself to be both rugged and reliable. These characteristics have contributed to its enduring popularity. Though production ceased in the FSU in the late 1960s, manufacture continues in a variety

of different countries. Well in excess of 50 million of these weapons or their copies have been made through the years (Jane's Defense Equipment and Technology 2010).

Figure 35 - AK-47 Assault Rifle (Jane's Defense Equipment and Technology 2010)

The AK-47 fires a standard 7.62x39 M1943 cartridge. Muzzle velocity for the standard 10 gram bullet is approximately 715 m/sec, though higher velocity rounds are available. The standard rifle is capable of firing up to 600 rounds per minute (Jane's Defense Equipment and Technology 2010). Effective range of the AK-47 is estimated to be 400 meters (Enemy Forces 2010).

The sheer number of produced weapons leads to wider availability. Many have found their way into the hands of insurgents. The ongoing demand for the weapons has kept its ammunition widely available. Its ease of use, rugged construction, and effectiveness has made it a weapon of choice for many nations.

2. UAV Detection by the Enemy

Maintaining surprise is critical in enhancing the effectiveness of a target engagement. In surveillance missions, stealth is necessary to prevent an adversary from deliberately modifying his actions, thereby reducing the validity of the surveillance data. When engaging with weapons, the element of surprise may prevent a target from taking evasive actions. For the purposes of this study, the targets are considered to be represented by males in their early twenties, with normal hearing and vision capabilities for this age group. As the targets are considered to be involved in IED activities, they are not equipped with any detection enhancement equipment, such as radar detection, IR imaging

systems, or binoculars. To determine maximum possible detection range, only the worst, or least stealthy, case is considered.

a) Target Optical Detection of UAV

Many studies have been performed through the years in an effort to determine a generic formula for determining the probability of aircraft detection by unaided human observers. None have proven completely accurate in all situations. The studies reviewed included various types of aircraft, sizes, and colorings, in a certain region of search. For the purposes of this investigation, the observer was assumed to know the general direction of aircraft approach, the aircraft was in the unobstructed sky, and the sky conditions were clear. Additionally, the aircraft was painted a dull gray, with purely diffusive reflective properties. Rather than attempting to determine a probability of observation, an estimation of worst case detection range was made.

The human eye may be thought of as a specialized detector. Its spectral response is between approximately 400 and 800μm. As discussed earlier, the primary source of natural light required for human vision is the sun. An illustration of an eye is presented in Figure 36. Light enters through the cornea and is focused by the lens onto the retinal surface at the rear of the eye. Two types of detectors are present on the retina: rods and cones. Cone detectors are used for photopic (daytime) vision and have the ability to sense colors. Rod detectors are used primarily for scotopic (low light) and peripheral vision. The center of cone detector spectral response is approximately 0.6μm, while the center of rod spectral response is approximately 0.5μm.

A specialized region at the rear of the eye is called the fovea. In this small area there are only densely packed cone detectors that provide the most detailed information of the image. The fovea includes a FOV of less than two degrees. In this high-resolution area, the normal visual acuity assumed for the design of optical instruments of 20/20 corresponds to a resolution of 0.291mrad (Kopeika 1998). The visual axis of the eye is aligned with this area, and the eye is in constant motion to pass the image across this sensitive area. The eye moves in jumps while searching and can only provide vision during periods of little or no motion. These stationary periods, termed fixations, are typically 0.25 seconds in duration (Koopman 1946).

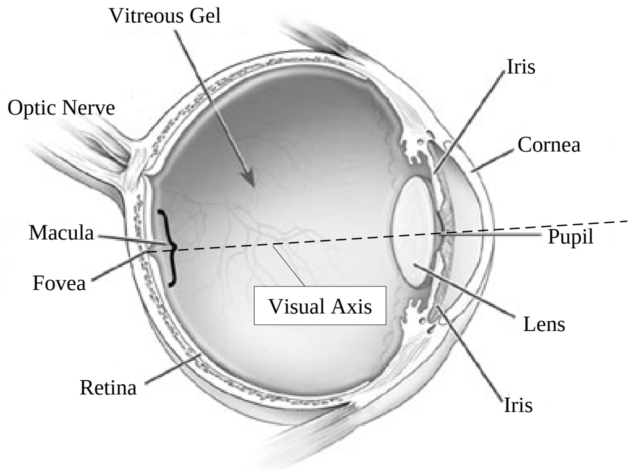


Figure 36 - Diagram of Human Eye (Savio D Silva Network 2010)

Outside of the fovea, visual acuity drops off rapidly with the number of cone detectors. Instead, rod detectors provide less sensitive, but still important, peripheral vision. At less than three degrees from fovea axis, visual acuity has decreased by fifty percent; at ten degrees, by eighty percent. This situation is illustrated in Figure 37. In this illustration, the angle from the fovea axis is noted by degrees, and the relative visual acuity for each angle is normalized to be a value between zero and one (Operations Evaluation Group 1952).

Acuity also depends on the available illumination. For maximum acuity, uniform illumination is needed to maintain fixed pupil dilation. In varying illumination, the iris opens wider as the brightness of the scene decreases. Vision results more from low-light rod detectors than normal-light cone detectors. As the rod detectors are spaced further apart, resolution abilities decrease (Kopeika 1998).

Color can also have an effect on visual acuity. Normally testing for acuity is done using white light. However, there are some effects of chromatic aberrations and acuity is improved for yellow and yellow-green lighting. In contrast, acuity decreases for reds, and may decrease by up to thirty percent for blues or violets. This is due to a lack of blue cone detectors (Kopeika 1998). Other studies had shown that for operational

problems of visual search, the effects due to color could be ignored without contributing to appreciable errors (Koopman 1946). Color will not be considered in this investigation. Studies by the Operations Evaluation Group indicated that the important factors in determining whether or not a target will be seen by the human eye in daylight reduced to:

- Target contrast against its background,
- Target distance from the eye,
- Size of the target (Operations Evaluation Group 1952).

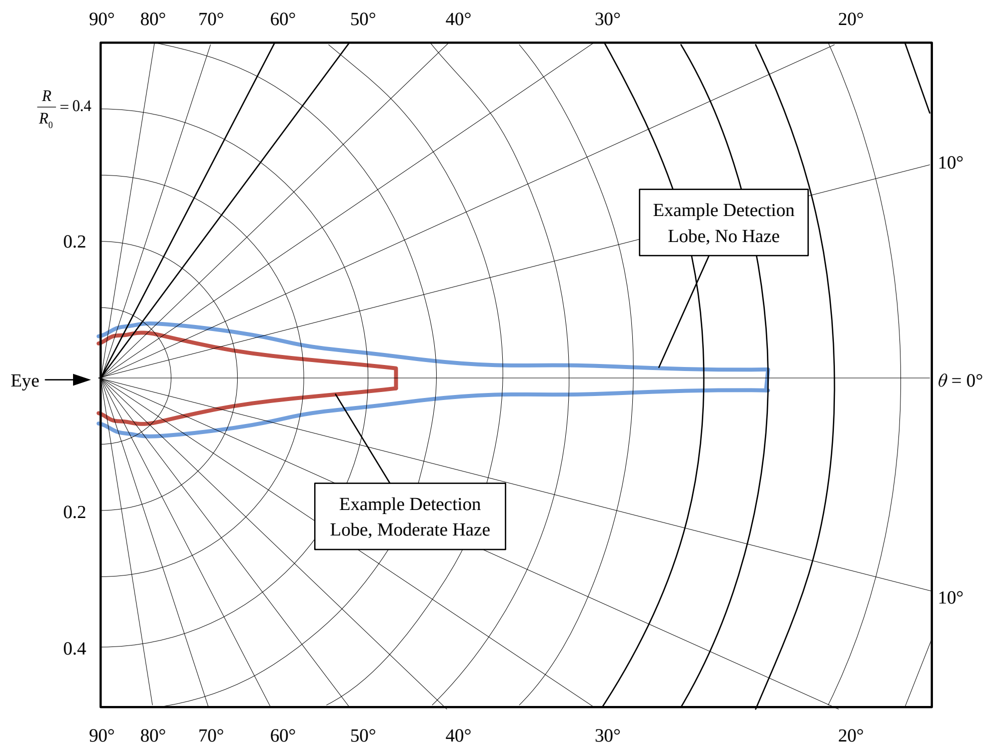


Figure 37 - Human Eye Detection Lobe from (Operations Evaluation Group 1952)

The target distance and size determine the solid angle subtended by the target image and thus the target image size on the retina. Studies performed to determine threshold contrast (the contrast at which fifty percent of all targets would be detected) used a simple circular shape that subtended the representative target angle rather than detailed target shapes. This data may be modified by "field factors" to determine a threshold contrast for a given angular subtense as experienced by the observer's eye (Taylor 1964).

Note that the term "contrast" as used here refers to a ratio of two luminance values and is dimensionless. The target size was given in milliradians, and was determined from the surrogate UAV wingspans divided by slant range as the UAVs traveled a straight and level flight path directly at the observer at a typical operational altitude of one thousand feet. The flight path was assumed to be in clear atmospheric conditions, with no structure background. A plot of the resulting target threshold contrast is presented as Figure 38.

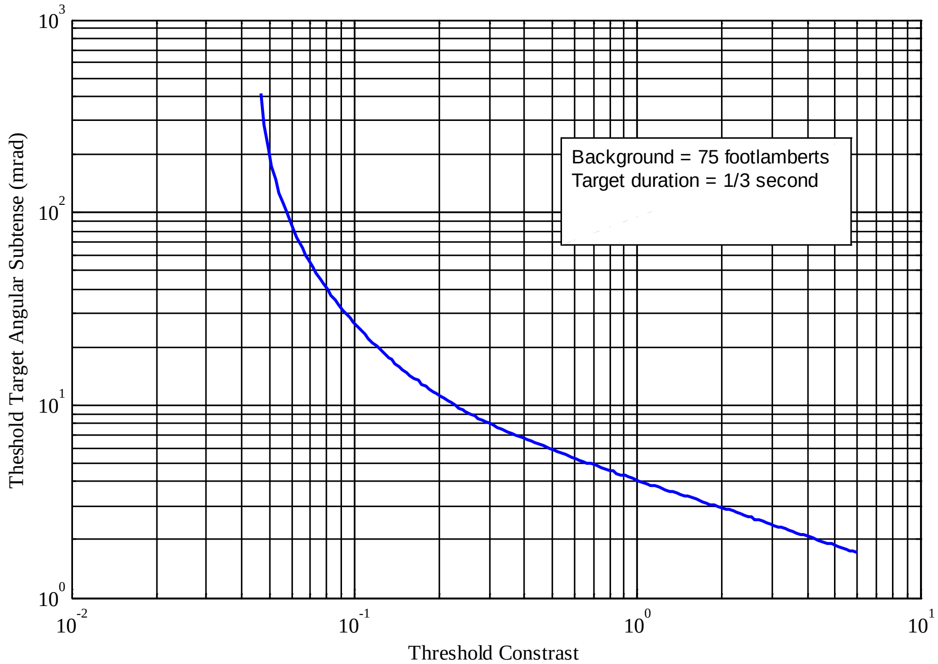


Figure 38 - Angular Subtense versus Threshold Contrast

The apparent contrast of the UAV against the sky background was derived using available study data and assumptions. There are three possible sources of luminance for the UAVs: direct sunlight, sunlight reflected from the terrain, and path (sky) luminance. As the slant range between the target and observer increases, the apparent contrast decreases as there is additional light scattering due to the increased path length. Some of the background light is scattered into the line of sight, while some of the light from the target is scattered from the line of sight. At longer slant ranges, the result is that the target and background begin to appear similar in luminance. In addition, there are atmospheric transmission losses. The apparent contrast, *C*, is defined as:

Equation 18 - Apparent Contrast Equation

Where::

τ is the atmospheric transmission,

B_h is the luminance of the sky from altitude *h* at a given angle of sight,

B_t is the inherent luminance of the target before attenuation

B_o is the luminance of the sky as it appears at zero altitude along the same angle of sight (Dugas 1965).

Transmission of the atmosphere and brightness of the daylight sky were derived from field test information (Boileau 1964). During this testing, the sun was at approximately 41 degrees from the zenith. The tabular data contained in the report were used as input tables to a Matlab® script that performed necessary interpolations and calculations.

The modeling script first determined target angular subtense as seen by an observer as a function of range and UAV altitude. The area of a circular disk of UAV wingspan diameter was calculated. The disk was positioned horizontally with the ground. As an observer on the ground would only be able to see the underside of the disk, the only source of illumination for the underside considered was the sunlight reflected off the terrain. The terrain was considered to be sand, and a reflectivity of 0.3 was used over all path angles. The disk was considered painted with a dull gray paint with a reflectivity of 0.26. In both cases, the reflective surfaces were considered to be perfectly diffusing. The total illuminance of the terrain by the sun and sky was considered to be 7,000 foot candles. Using the preceding data, the luminance of the UAV was estimated as the product of the illumination on the scene and the reflectivity of both the terrain and target

for each of the observation angles. From this, apparent contrast values for the UAVs at points throughout the flight path were determined.

The apparent contrast values derived above were used as an index into the data array used for developing the angular subtense versus threshold contrast chart presented earlier. From this mapping, a determination of the angular subtense required was determined. This value was then mapped to a range using the angular subtense versus slant range data developed during the first step. The resulting graphs have two lines, one indicating the angular target size as a function of slant range, and the other, the threshold size as a function of slant range derived from manipulation of threshold contrast values. The intersection of the two lines indicates that the expected maximum range UAV detection will occur with a probability of 99 percent (Dugas 1965).

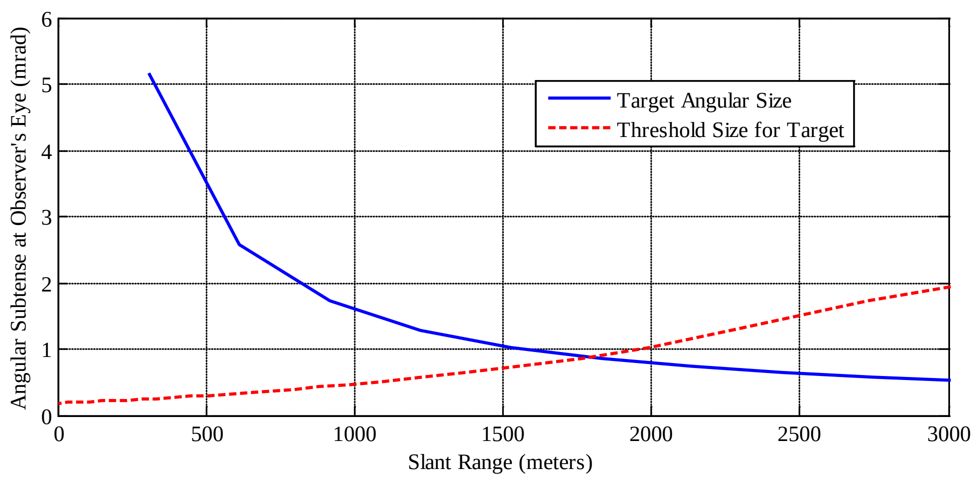


Figure 39 - Tier I Maximum Detection Range Determination

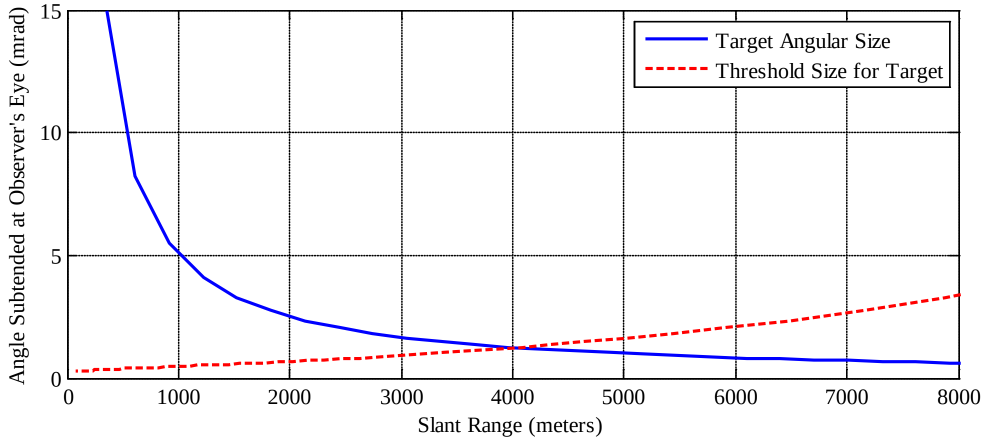


Figure 40 - Tier II Maximum Detection Range Determination

From Figure 39, the unaided visual detection of the Tier I surrogate UAV by a person with 20/20 vision should occur at approximately 1,800 meter slant range (~5,900ft), with the target subtending an approximate 0.9 mrad. Similarly, the detection of the Tier II surrogate UAV should occur by a slant range of approximately 4,000 meters (~13,000ft), with an angular subtense of 1.2 mrad as shown in Figure 40.

b) Target Audible Detection of UAV

A sound is generated when an object vibrates. This vibration causes the molecules next to the object to vibrate, those molecules then pass the vibration to the molecules next to them and this process continues until the vibration loses all of its energy.

The human ear is an entirely mechanical device that converts pressure disturbances propagated through the atmosphere into electrical signals that the brain can process. A sound is generated when an object vibrates. This vibration causes the molecules next to the object to vibrate, those molecules then pass the vibration to the molecules next to them and this process continues until the vibration loses all of its energy. The human ear is made up of three parts, the outer ear, the middle ear and the inner ear. The outer ear consists of the pinna and ear canal. When a pressure wave hits the outer ear, it is funneled through the ear canal and focused onto the ear drum. The middle ear consists of the ear drum and ossicles. The ear drum picks up the vibrations and passes the vibrations to the inner ear by vibrating the ossicles or ear bones. The ear drum and

ossicles act as an amplifier for the inner ear. The inner ear consists of the cochlea and auditory nerve. When the vibrations make it to the inner ear they cause tiny hairs in the cochlea to displace, resulting in an electrical signal that is passed to the auditory nerve. The auditory nerve delivers the electrical signal to the brain were it is processed into a sound (Harris 2011). Figure 41 shows a cross-section of the human ear.

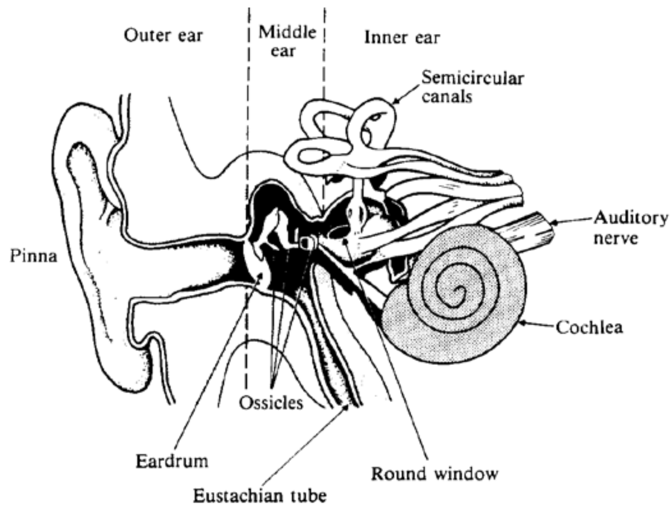


Figure 41 - The Human Ear (Chan 2008)

The noise generated by a UAV was investigated to determine the range it would be susceptible to audible detection by a representative twenty-year-old male with no hearing loss. For UAVs there are two sources of noise, the first being the propeller and the second, the engine. When a propeller moves through the air, it generates vibration and displacement of the surrounding air. For non-electric motors, the sound of gasoline combustion and piston movement will also generate noise.

Propellers generate noise in a spherical pattern similar to the shock waves of an explosion. The noise generated from a propeller is a function of its top speed, power input and diameter. Equation 19 is used to calculate propeller noise for commercial aircraft (Marte and Kurtz 1970).

Equation 19 - Propeller Noise Calculation from (Marte and Kurtz 1970)

where:

= rms sound pressure level in dynes/cm2

m = order of the harmonic

S = distance from propeller hub to observer, ft

R = propeller radius, ft

A = propeller disc area, ft^2

P_h = absorbed power, horsepower

T = thrust, lb

B = number of blades

M_t = tip Mach number

J_{mb} = Bessel function of order mB

x = argument of Bessel function 0.8 M_t mB sin Ø

Ø = angle from forward propeller axis to observer

Current UAV propellers have a noise level of roughly 65–70 decibels (dBA) at 100 ft (Miller 2001). The current propeller is a nylon propeller with two blades and a typical wing airfoil. Recent studies have determined that by increasing the number of blades, changing the airfoil, and changing the blade material, a UAV propeller noise profile can be reduced by 12 dBA.

The blade material of a propeller can be changed to a softer but stronger plastic. The increased strength will result in less vibration during vortices shedding. The softer material will absorb some of the sound and result in a softer sound. The new materials are expensive, but the increased strength will result in longer life spans and fewer breaks during arrested landings.

The number of blades used for a propeller requires a number of tradeoffs. For smaller electric engines there is a large drop in efficiency due to the higher speeds and

reduced torque. For four-stroke and two-stroke engines, the loss in efficiency is not as severe because of lower rotational speeds and higher torque. As the number of blades increases, the noise produced drops, making this a good option for larger Tier II UAVs but not for the smaller Tier I UAVs.

Propeller noise is driven by tip shape; rounded tips result in less noise than sharp tips. The proposed airfoil (Miller 2001) takes advantage of this concept over the length of the blade resulting in significant noise reductions. The propeller must be chosen based on the engine, performance requirements and noise requirements of the UAV. Figure 42 shows the sound profile for a typical UAV propeller. Note that the top axis is decibels with the X and Y axis in feet.

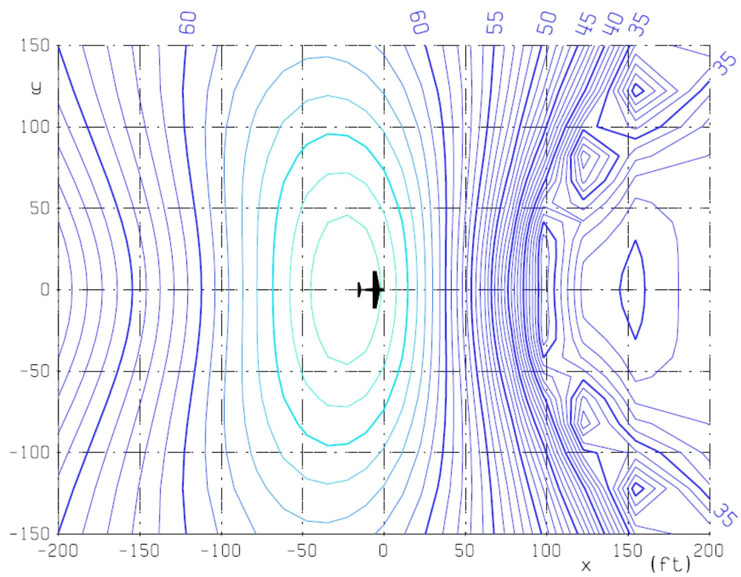


Figure 42 - UAV Noise Profile from (Miller 2001)

The noise made by a UAV must remain below the background noise level or 0 dB to remain unheard. Assuming the worst case scenario, being heard in a remote location standing on a hard surface with little to no background noise or wind, the sound level would have to be 0 dB. To calculate the drop in noise per unit length, the Stokes equation was used. Equation 20 shows the Stokes equation for sound attenuation.

From SBIR N02-096 (DTIC 2001), the noise level for a Tier 2 UAV is assumed to be 68 dB at 33 meters at 2,000 Hz. From measurements of two-stroke motors, the engine is assumed to produce 85 dB at 50 ft (Jackson Hole Scientific Investigations 2002). The Tier 1 UAV is assumed to produce 40 dB at 2,000 Hz. The air density, sound speed and dynamic viscosity were assumed for Kabul, Afghanistan. Figure 43 was derived by the RUINS team to depict the results of the study.

$$\alpha = \frac{2(\eta + \eta^v)\omega^2}{3\rho V^3}$$

Equation 20 - Stokes Equation from (Silex Innovations 2002)

Where

α = Sound attenuation in air (neper/m)

η = Dynamic viscosity of air (Pascal-s)

= Volume viscosity of air (Pascal-s)

ω = Frequency (cycles/second)

ρ = density (kg/m^3)

V = Speed of sound through air (m/s)

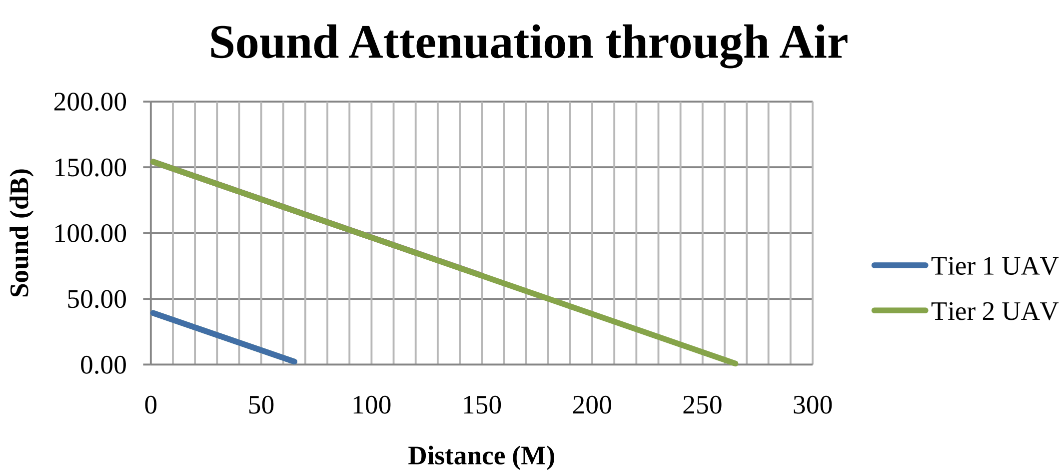


Figure 43 - Sound Attenuation through Air

There are many considerations for the audible detection of UAVs. In a moving target scenario, the engine noise in the cabin of the vehicle would make audible detection of the UAV before it enters striking range very unlikely. In the fixed target scenario, urban background noise levels will increase the detection threshold significantly. In either case, audible detection is not anticipated until the UAV is well inside the AK-47 range.

C. Target Engagement Envelopes

Using data developed during the preceding analyses, graphical models were generated of UAV-target weapon engagement for the stationary scenarios. These models integrated 1) the scenario UAV flight elevations, 2) the identification ranges necessary to obtain firing authority for the 1.0 meter and 3.5 meter targets using both the EO and IR imagers, 3) the range of enemy unaided visual detection of the UAVs, and 4) the effective ranges for the enemy AK-47 and RPG-7 defensive weapons.

For the enemy defense weapons, a fixed effective range was used regardless of the weapon firing angle. The effective range for the RPG-7 was selected as 300 meters as previously described; the effective range for the AK-47 was 400 meters. While a gunner may be able to hit a target at the longer ranges, the probability is lower due to the smaller UAV angular subtense presented resulting from range. As range decreases, the probability of hitting the UAV increases with apparent target size. No estimations of such changes in probability were included.

No estimation of engagement ranges using MANPADS was performed due to the unknown signatures of the UAVs and the associated sensitivity of the missile systems. If the signature of the UAV is sufficient, the MANPADS will be able to engage the aircraft at the maximum visual detection range.

The resulting graph presents a simplified model of the target engagement envelope. In both the graphical depictions and all detection calculations, the UAV was assumed to be maintaining a fixed altitude while navigating an azimuth course directly at the target at a fixed speed. Evasive maneuvers were not considered for this study.

1. Tier I Engagement Envelope

The Tier I UAV was found to be well outside the threat range of the AK-47 rifle at the unaided visual detection range regardless flight altitude (Figure 44). The Tier I EO sensor system proved capable of positive identification and weapons deployment of either the 1.0-meter or 3.5-meter target while remaining outside of both the AK-47 and RPG-7 effective ranges. However, identification of the 1.0-meter target using the IR sensor system did not occur until well within the effective range of both the AK-47 and the RPG-7.

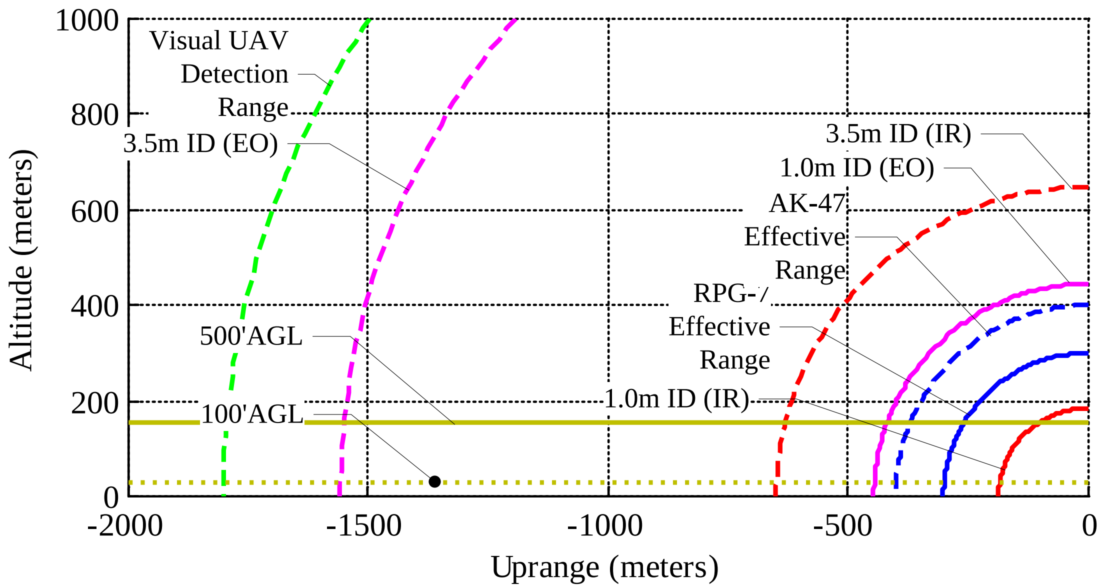


Figure 44 - Tier I Engagement Envelope

An analysis was performed to determine the amount time the aircraft is subject to enemy defenses during a possible weapon engagement. The entries in the tables indicate the times, in seconds, that the UAV was traveling certain portions of its profile and the associated enemy defense risk. In all of these determinations, the UAV was considered to be headed directly at the target while maintaining its flight altitude. The results are presented in Table 20.

Table 20 - Tier I Susceptibility - Engagement Times for Scenario Flight Conditions

Event	Seconds at 30 knots UAV Airspeed	
	100 feet AGL (30.5 m)	500 feet AGL (152.4 m)
Time from maximum enemy visual detection of UAV until overhead target	113	113
Time from maximum visual detection range until within AK-47 range	88	89
Time from ID using 3.5m EO until within AK-47 range	73	74
Time from ID using 1.0m EO until within AK-47 range	3	3
Time from ID using 3.5m IR until within AK-47 range	16	16
Time from AK-47 max range until ID using 1.0m IR[1]	14[1]	17[1]
[1] 1.0 ID (IR) range not reached until after AK-47 effective range reached.		

2. Tier II Engagement Envelope

The Tier II UAV was found to be well within the visual detection range prior to entering the AK-47 maximum effective range (Figure 45) regardless of flight altitude. On any of the two flight profiles, either the onboard EO or IR sensor could identify both the 1.0-meter and 3.5-meter targets while well outside of the range of both the AK-47 and RPG-7.

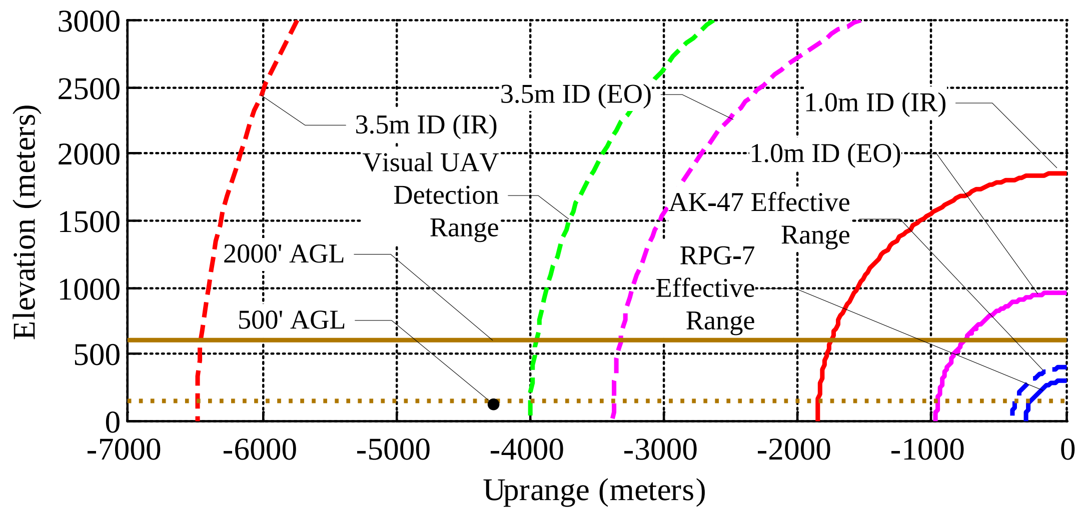


Figure 45 - Tier II Engagement Envelope

Similar to Tier I, an analysis was performed to determine the amount time the aircraft is subject to enemy defenses during a possible weapon engagement. The results are presented in Table 21.

Table 21 - Tier II Susceptibility - Engagement Timing for Scenario Flight Conditions

Event	Seconds at 65 knots UAV Airspeed	
	500 feet AGL (152.4 m)	2,000 feet AGL (609.6 m)
Time from maximum enemy visual detection of UAV until overhead target	123	122
Time from maximum visual detection range until within AK-47 range	112	122
Time from ID using 3.5m EO until within AK-47 range	93	103
Time from ID using 1.0m EO until within AK-47 range	18	23
Time from ID using 3.5m IR until within AK-47 range	189	199
Time from ID using 1.0m IR until within AK-47 range	46	54

3. Engagement Limitation Summaries

Several observations may be made from the preceding discussion to aid in the selection of an optimum solution.

- Sensor performance characteristics are geometric calculations assuming perfect optics, no background clutter, and no range attenuation effects. Detection performance of actual sensors will likely be reduced.
- The AK-47 was considered the primary enemy defensive weapon of concern.
- If the signature of the UAVs was sufficient to launch a MANPADS, the MANPADS engagement range exceeded most of the identification detection ranges of any of the onboard UAV sensors, regardless of Tier, as launch could occur at the enemy visual UAV detection range. The sole exception was the Tier II 3.5-meter target detection using the IR sensor.
- All estimations of visual detection range were based on worst case (clear, day-time) conditions. Visual detection ranges are expected to decrease significantly at night and lower visibility conditions. In partial moon night conditions with no external lighting, visual UAV detection may prove impossible regardless of range or flight altitude.
- The Tier II UAV IR sensor outperformed the EO sensor. This was due to the pixel size of detector arrays being nearly identical, but EO optical FOV being more than twice as large as the IR FOV.
- The Tier II UAV was able to identify both the 1.0-meter and 3.5-meter targets using either the EO or IR sensor outside of enemy defense ranges.
- The Tier I UAV was within the effective range of an AK-47 for a period of time prior to achieving the adequate sensor resolution required for weapon deployment against the 1.0-meter target when utilizing the current IR sensor. The low resolution of the Tier I IR sensor and slower flight speed contributes to susceptibility durations prior to identification; however, its smaller size also decreases the probability of effective enemy defense.
- The threat exposure necessary to accomplish positive identification using the IR sensors of the Tier I UAV would indicate use of this targeting sensor only in

reduced visibility conditions (night) to reduce UAV susceptibility to enemy defenses.

- Calculations indicated the Tier I UAV audibly detectable while on the 100' AGL flight path, and undetectable at 500' AGL. The Tier II UAV was calculated to be audibly undetectable while flying on the 2,000' AGL flight path.
- The optimum weapon engagement would consist of the UAV dispensing its weapons at ranges beyond the enemy's detection and self-defense ranges. This situation would allow surprise engagement of the enemy, minimizing the time available to react and reposition, as well as minimizing the possibility of damage to the UAV resulting from enemy self-defenses by remaining outside of effective enemy defense range. Table 22 presents the detection ranges developed during the analysis of possible UAV-enemy engagements. Unfortunately, the maximum range for proper identification necessary for a firing decision was estimated to be less than the visual detection range, with the single exception of the Tier II 3.5-meter target identification. The UAVs will likely be visually detected by the enemy prior to weapon engagement.

Table 22 - Calculated Detection Ranges

UAV Type	Maximum Range for Identification (meters)		Range of UAV Detection by Enemy (meters)	
	Vehicle	Human	Visual	Audible
Tier I	1,556	444	1,800	65
Tier II	6,487	1,853	4,000	265

D. Identification of Alternatives

The development, evaluation, and selection of alternatives are a fundamental concept in the system engineering process. Most engineering problems involve managing constrained resources to develop a set of alternatives that will be compared to a standard or each other. Once a selection method is established, a decision between the alternatives can be made (Blanchard and Fabrycky 2006).

Blanchard and Fabrycky explain that limiting and strategic factors must be identified to define alternatives. While limiting factors are those that “stand in the way of attaining objectives,” strategic factors are those “that can be altered to make progress possible.” For this project, the primary limiting factors considered were the available payload weights and the sensor resolution of the typical sensor packages available on small UAVs. Strategic factors included weapon type and weapon release range. These were developed using research, analysis, and stakeholder feedback (Blanchard and Fabrycky 2006).

To properly compare alternatives, they must be converted into “a common measure” (Blanchard and Fabrycky 2006). The final comparison of alternatives was performed using a combination of analysis and modeling. However, possible alternatives were identified and their feasibility verified prior to reaching that stage. The limited alternatives identified during this process were then evaluated, using a variety of methods, before the optimum solutions were selected.

1. Weapons Alternatives

Several types of weapons were considered for use in the RUINS project. These included 1) guns, 2) unguided ballistic weapons, 3) guided ballistic weapons, 4) unguided propelled weapons, and 5) guided propelled weapons. The characteristics of each general type of weapon were examined to gauge their applicability to the project.

The field of weaponeering was introduced earlier. Certain basic concepts from elementary weaponeering could be used in the assessment of various weapon types for use with the UAV surrogates. One of the major parameters of weaponeering, *SSPD*, has already been discussed. Though direct determination of *SSPD* was not believed possible for the project due to lack of data, the measures of delivery accuracy used in its development were believed useful for solution comparisons.

When attacking a target on the ground, an air vehicle will attempt to deliver the weapon to the ground aim point, referred to as the desired mean point of impact (DMPI). The actual impact points of the weapons will be dispersed around the mean point of impact (MPI). The disbursements around the MPI will be due in part to ballistic dispersion, the

result of small manufacturing differences between individual weapons, and weather. Only unguided weapons display ballistic errors. The difference in location of the DMPI and the MPI is due to aiming errors. The two types of errors are assumed to be independent random variables, with the total miss distance being the sum of the ballistic and aiming errors. The miss errors are generally measured in either the range or deflection (cross range) directions. Figure 46 illustrates these terms (Driels 2004).

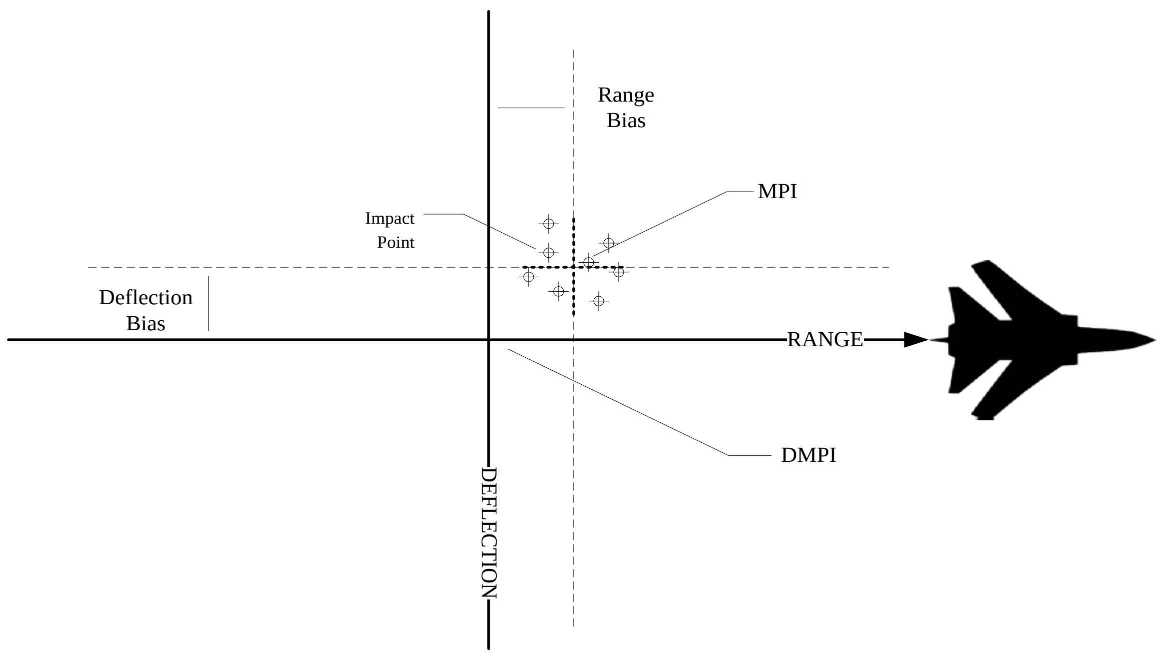


Figure 46 - Weaponeering Reference Terms (Driels 2004)

Three other terms are used to further describe the impact errors. Rather than using standard deviations, range error probable (REP) and deflection error probable (DEP) are typically used. According to Morris Driels, “The REP is the distance from the DMPI to one of a pair of lines perpendicular to the range direction, equidistant from the DMPI such that 50% of the impact points lie between them.” DEP is a similar construct in the deflection (cross range) direction. Both are calculated only after careful analysis has removed any biases and extreme cases from the data. Also commonly used is circular error probable (CEP), which is based on a circle centered on the DMPI constructed with 50

percent of the impact points contained within its boundary. REP and DEP are generally more useful, as CEP may be derived from them; however, the inverse is not true (Driels 2004).

Though the preceding descriptions of REP, DEP, and CEP focused on ground measurements, in some cases such measurements may be made in either a plane normal to the line of sight of aircraft and target at time of weapon release, or the weapon velocity vector at the time of impact. Conversion between the ground and normal plane measurements is performed with the application of geometric principles (Driels 2004).

a) Unaccelerated Unguided Weapons

Several types of accelerated weapon deliveries that affect the weapon trajectory are possible. Aircraft maneuvers prior to release may cause the weapon to be accelerated and increase its engagement range. These include pull-up, lateral toss, and loft maneuvers. However, none of these maneuvers are being considered for the UAV platform. The UAV flies in a fairly benign flight path, with gradual turns and few, if any, dives. As a result, the following discussion will include only unaccelerated deliveries. For the purposes of this discussion, the UAV will be limited to horizontal flight at a fixed speed. When dispensed, the weapon motion will be in a plane containing the velocity vector of the UAV at release (Driels 2004).

The motion of the weapon is assumed to be independent in the horizontal and vertical directions once released from the UAV. Further, the velocity of the weapon at the time of dispense is also known, and will include horizontal and vertical components from the UAV forward velocity and any weapon ejection velocity. In many higher-speed situations, ejection charges are necessary to force the weapon from the boundary layer near the aircraft. Without this positive ejection, large accuracy errors may result (Driels 2004). Such charges will not be considered on the Tier I and II UAVs due to their lower airspeeds.

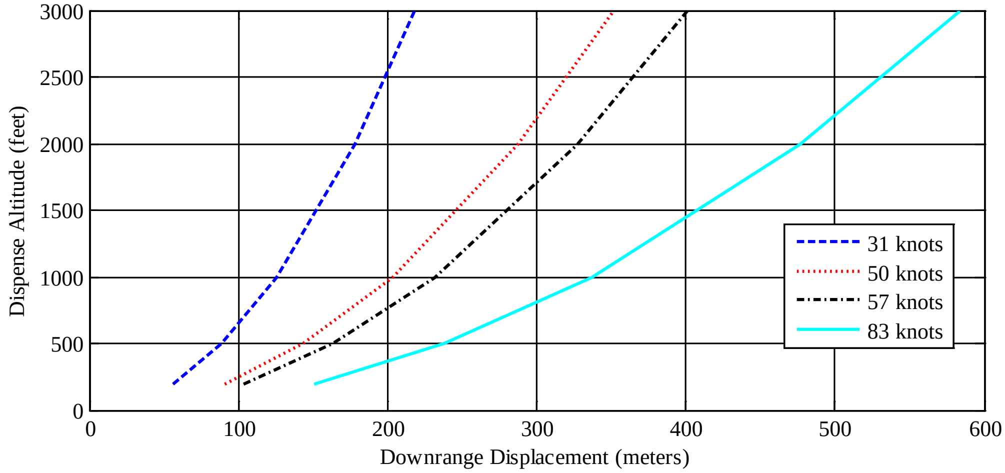


Figure 47 - Downrange Displacement for Ballistic Dispense from Surrogate UAVs

A simple point mass, zero-drag model may be used to determine the maximum standoff range for successful targeting engagement and the maximum weapon velocity at impact. As this model neglects the effects of aerodynamic drag on any released weapon, the actual standoff ranges and impact velocities will be lower. Figure 47 and Figure 48 show the results of such calculations using the anticipated surrogate UAV cruise and maximum velocities. In all cases, a level flight profile was assumed.

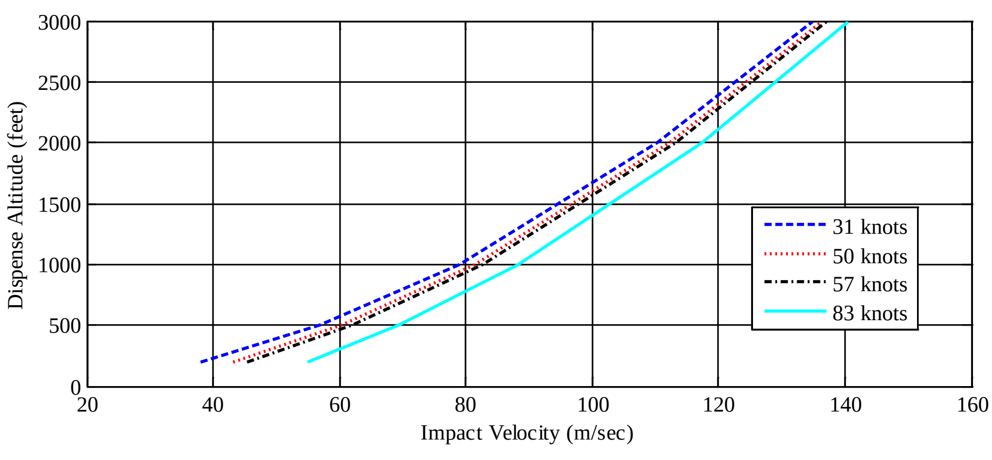


Figure 48 - Impact Velocities of Ballistic Dispense from Surrogate UAVs

Delivery accuracy for unguided ballistic weapons is influenced primarily by the dispensing aircraft. As there is no guidance available in the weapon; the accuracy

depends on the aircraft releasing the weapon at the proper time and location, derived using aircraft current position, flight speed, heading, and attitude. Also impacting the accuracy are the effects of any winds. Though the dispensing aircraft avionics may be able to accurately determine wind speed and perform adjustments to release timing with the aid of a wind model, there is no information on how the winds may vary between the weapon release location and point of impact. Even small magnitudes of unpredicted wind can shift the final impact point, and the problem becomes more significant with increasing dispense altitude. Any targeting model must adequately compensate for wind effects (Driels 2004).

Several methods may be used by a fire control computer (FCC) for utilizing sensor data to assist the pilot in releasing the weapon in the proper location at the proper time. Three typical methods will be discussed. Each requires knowledge of the aircraft flight state and understanding of the ballistics of the weapon to be deployed to plan an accurate release (Driels 2004).

In the continuously computed release point (CCRP) method, the pilot selects the target before reaching the release point. The FCC then determines the aircraft altitude above the target and ground range by use of onboard sensors, such as a laser rangefinder. Using the designator depression angle and known altitude, the FCC cues the pilot to the proper release point where the weapon is released automatically (Driels 2004).

The continuously computed impact point (CCIP) method indicates where the weapon would hit the ground if released at that moment. The FCC is primarily used as a sophisticated display manager to constantly update the pilot's display for current position. The weapon is manually released by the pilot when FCC display cues are properly aligned with the target (Driels 2004).

The bombing on coordinate (BOC) method is well known but has become much more effective with the introduction of the global positioning system (GPS) instrumentation in modern aircraft. In this method, the GPS coordinates of a target are known and input into the weapon, either prior to release or during flight. The aircraft is flown toward the target location. The FCC computes the bomb fall range and the weapon

is released at this range from the target. The weapon then guides itself to the preselected coordinates (Driels 2004).

Sources of error in the delivery of these types of weapons are many. In any of the methods, a slight error in dispense timing can cause the target to be missed. Some of the error sources include slight aircraft positioning errors (yaw, pitch, roll), slant range measurement errors (range, relative depression angle), and altitude measurements (Driels 2004). Another source of error may be the time delay in the data link communication necessary for transmitting a dispense command to the UAV. Further analysis of resulting errors may be necessary to fully understand the limitations of the unguided ballistic methods.

b) Unaccelerated Guided Weapons

An advantage of guided weapons is that the accuracy of their delivery is due to the weapon guidance system and generally independent of the dispensing aircraft. As these types of weapons have guidance effects that occur during descent, ballistic dispersion is not applicable. A guided weapon will reach the target if it is released within a volume called the launch acceptable region (LAR), illustrated in Figure 49. Demands on air crew for the precision of weapon release at the ballistic point are decreased (Driels 2004).

Guidance is implemented by deflection of some surface in the airstream to control the velocity vector of the weapon. This can range from a simple single fin to more complex guidance that proportionally displaces fins at the minimal angles to perform needed steering, reducing speed loss and maintaining maximum kinetic energy. Several sensor types are used for guidance. For use with a UAV system, all systems currently under consideration are passive. These include imaging sensors, EO and/or IR modulated detector sensors, laser sensors, inertial sensors, and passive RF. Active RF systems are not under consideration due to their higher weight resulting from needed transmitters.

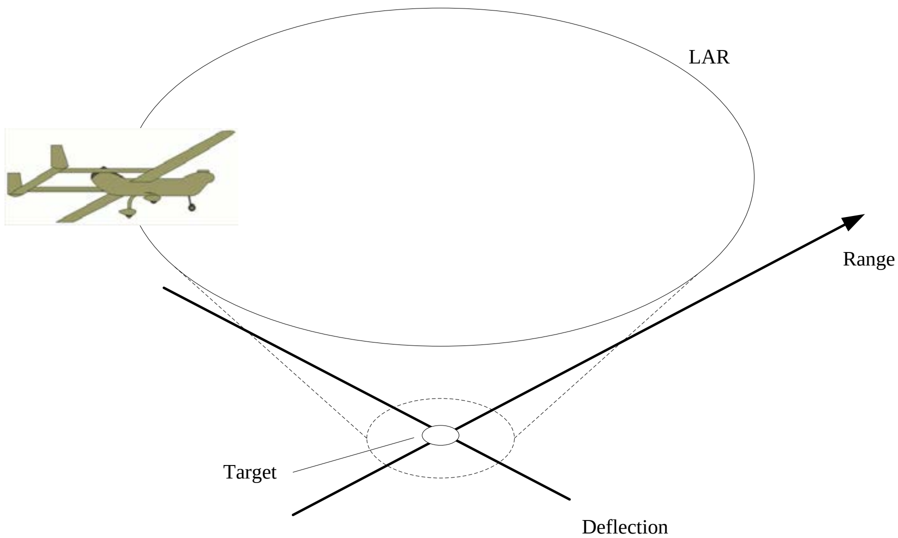


Figure 49 - Launch Acceptable Region (Driels 2004)

While guidance provides a benefit in accuracy, it is not without cost. Due to the increased complexity of the added guidance system, guided munitions are more costly than their non-guided counterparts. A portion of their weight is used by the guidance system including sensors, processing, and steering mechanisms, all of which decrease the weight available for use in the warhead. Any necessary power needed for electronics and fin deflections must also be provided onboard the weapon. Most guided ballistic weapons will also have a decreased range and impact velocity when compared to unguided weapons, resulting from the loss of velocity caused by steering fin aerodynamic drag. An exception to this would be a guided weapon with glide capabilities such as the Small Diameter Bomb.

For a guided weapon, some mechanism must be in place to calculate a path between the weapon's current position and the target. The general methods used separate the guidance types to either one that guides to a point in space, or one that guides to a target.

To guide to a point in space, the target's location must be known. Any target movement, unless at a known fixed rate and direction, renders this method inadequate. Little is required for performing this type of guidance other than some sort of

navigation system that can calculate current position and a processor that can convert the current weapon trajectory information and target location into steering corrections. GPS- and inertial-guided weapons use this method.

Moving and fixed targets may be engaged by a weapon that guides to target, but additional equipment onboard the weapon is necessary. This may be accomplished by either remote control of the weapon guidance or tracker guidance. Remote control requires commands to be sent to the weapon. These may be transmitted by radio, laser, or wire. These systems are very accurate but require man-in-the-loop feedback throughout their flight to ensure proper guidance. In comparison, tracker guidance may be performed autonomously once the target has been acquired. This type of guidance uses some form of sensor system to dynamically track the target, as the weapon completes its trajectory and generates the necessary steering commands to remain on course.

c) Guns

A wide variety of weapons are classified as guns for this investigation, with all including both the actual firing mechanism and the ammunition. The delivery of a projectile from a gun is often modeled as a straight line for shorter ranges from the aircraft to the target. The effective range of guns may range from under 100 yards for a shotgun to nearly a mile for larger caliber rounds. The effective radius of rounds that might be used on a UAV also varies widely, from small .22 caliber rounds to explosive, fleshette-equipped 40mm mortar rounds.

Aiming of a gun mounted on a UAV might be accomplished using a variety of methods. A gimbaled mount would allow the gun aim point to separate from the UAV velocity vector, accommodating the slow maneuverability of the UAV platforms. However, this addition would be at the cost of much added weight. Mounting the gun in a lookdown position and coupling with automatic UAV maneuvers for sighting is another option. In either case, feedback to the operator on aiming location could be provided by the FCC.

Limiting considerations of guns are stresses to the UAV, weight concerns, and targeting accuracies. Stresses to the airframe, due to the absorption of impacts

resulting from each gun firing may stress the UAV airframes in ways that designers never considered. The weight of the firing components of a gun, including the barrel, magazines, receivers, and any other necessary components, can be considerable. The weight of any necessary gimbaled mounting needed for proper aiming must be considered, as well as the weight of any ammunition. Of this total weight, only a small fraction is delivered to the target.

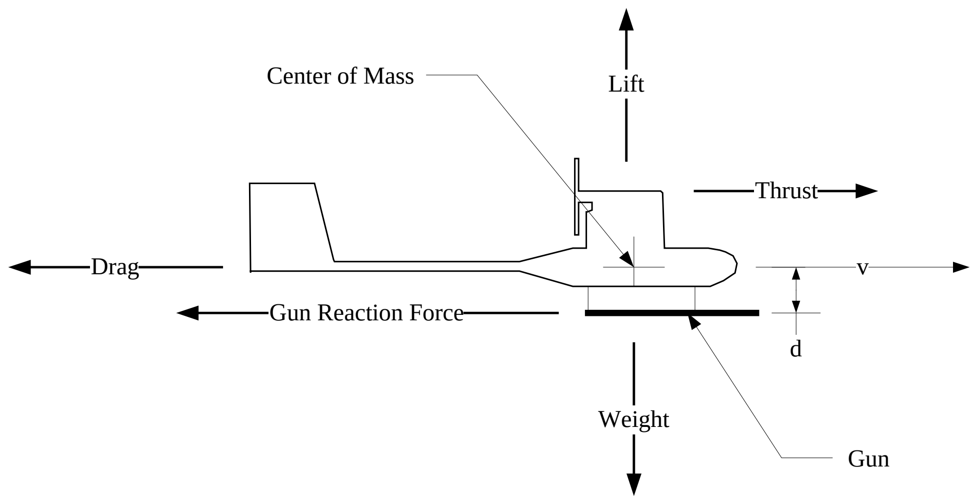


Figure 50 - Gun Physics Issues

Targeting accuracy of shots may be affected by the firing of a gun. When the projectile leaves the barrel of the gun, it leaves with a certain amount of kinetic energy. For conservation of energy, an equal and opposite amount of energy will be absorbed by the UAV as recoil, potentially applying a torque and shifting the aim point of the gun. The FCC must be able to make the required corrections to the gun aim and flight trim as a result of these. This problem could be minimized or eliminated by positioning the gun such that the recoil acts near or at the center of mass of the UAV. However, this could require significant modifications to the UAV. Figure 50 illustrates the various physical forces operating on the UAV at the time of a gun firing.

d) Accelerated Unguided Weapons

Accelerated unguided weapons are unguided rockets. The accuracy is subject to ballistic dispersion as these systems have no guidance. Trajectories of these types of weapons are considered to be on a straight line between the aircraft and target and

at high speed. The FCC operates similarly to the CCIP bombing mode in prompting the pilot for firing. While no weight is taken by guidance, a portion of the available weapon weight is used for rocket propellant, nozzles, and guidance surfaces.

There are advantages to unguided rockets when compared to unguided unaccelerated weapons. The addition of propulsion allows the standoff range from the aircraft to the target to be increased dramatically, providing for increased safety of the aircraft. The addition of acceleration to the weapon flight also increases the kinetic energy of the weapon, allowing for better target penetration. An improvement over guns, which may be considered similar weapons, is that the majority of the weight required by the weapon is deployed at the target and not maintained on the airframe. Further, the stresses to the UAV airframe from the firing of a missile are minimal, as the missile is either ejected from its carrier prior to rocket ignition or accelerates off its launcher at ignition.

A consideration when using a rocket propelled weapon is the blast effect that the firing aircraft experiences when the rocket motor fires. This effect may well prevent the use of unguided rockets from a UAV, as these types of weapons rely on initial aiming provided by the launching hardware.

A disadvantage of rockets, compared to unguided ballistic weapons, is the loss of weapon weight to rocket motor. Additionally, the flatter trajectory of unguided rockets provides for miss distance increases when deployed at low angles of flight. However, these disadvantages would seem to be adequately compensated for by the increased standoff range and higher energy delivered by this type of weapon.

e) Accelerated Guided Weapons

These types of weapons have the advantages of the unguided accelerated weapons coupled with the benefit of guidance. They provide significant standoff range as well as after-launch guidance capabilities. These weapons are also the most expensive, difficult, and time consuming to develop, require a more sophisticated FCC and operator interface, additional maintenance, and special handling procedures. The stresses

experienced by the UAV airframe from these types of weapons are the same as those of their unguided counterparts, both of which are less than that due to guns.

Another type of accelerated guided weapon could be the UAV itself in a role where it would destroy itself upon reaching the target. This option may be feasible for the Tier I UAV due to its limited payload and expendable nature. The available payload space could be filled by a warhead of some type and the UAV flown under direct operator control into the target. Though the impact energy of the UAV would not be great, due to its relatively low speed, it could be aimed quite accurately, due to the high maneuverability of the UAV and the pilot in the loop. A rocket assist may be possible to increase the impact airspeed, but the weight required for such a motor would decrease the available weight for a warhead. There may be legal prohibitions against this type of UAV weapon; however, the option will be retained for the purposes of the study.

2. Weapons Choice Tradeoffs

Building on the introductory analysis developed in the preceding section, a high level examination of the operational advantages and disadvantages of various weapon types was performed. Results of the examination are presented in Table 23, Table 24, and Table 25. The discussion of weapon types was non-specific with no particular make and/or model identified in an effort to determine all possible solutions for the UAV implementation. Further analysis was performed during the Evaluation of Alternatives phase.

Table 23 - Possible UAV Weapon Types - Unaccelerated

Weapon Type	Guidance	Advantages	Disadvantages
Unaccelerated	None	Low cost Ease of manufacture Maximum warhead payload	Ineffective against moving targets Subject to weather effects Minimal standoff range Large targeting errors possible
	GPS	Relatively low cost Ease of manufacture More accurate targeting Autonomous once deployed	Ineffective against moving targets Minimal standoff range Reduced warhead payload Increased maintenance Increased interface complexity Easy to jam
	Active Homing (Laser, Radar)	Relatively low cost Technology well known Accurate targeting May be used against moving targets Lock-on after launch possible Difficult to jam	Minimal standoff range Reduced warhead payload Increased maintenance Increased interface complexity Requires post-launch illumination

Table 24 - Possible UAV Weapon Types - Guns

Weapon Type	Guidance	Advantages	Disadvantages
Guns	None	Technology well known Increased standoff range May be used against moving targets Lower cost Low collateral damage	Reduced weapon effect Unknown long-term effects on airframe Sighting problems Low effect/weight ratio Reliability issues Absorption of kinetic energy

Table 25 - Possible UAV Weapon Types - Accelerated

Weapon Type	Guidance	Advantages	Disadvantages
Accelerated	None	Relatively low cost Ease of manufacture Increased standoff range Autonomous once deployed Technology well known Marginally effective against moving targets	Subject to weather effects Large targeting errors possible Decreased warhead payload
	GPS	More accurate targeting Autonomous once deployed Increased standoff range Technology well known	Ineffective against moving targets Decreased warhead payload Increased maintenance Increased interface complexity
	Active Homing (Laser, Radar)	Technology well known Accurate targeting Increased standoff range May be used against moving targets Lock-on after launch possible	Reduced warhead payload Increased maintenance Increased interface complexity Requires post-launch illumination Higher cost
	Passive Homing (Visual, IR)	Technology well known Accurate targeting Increased standoff range Effective against moving targets Autonomous once deployed	Reduced warhead payload Increased maintenance Increased interface complexity Highest cost Lock on before launch only

E. Candidate Weapon Identification and Preliminary Screening

A search of open source literature was performed to identify possible weapons that might be applicable to the RUINS application. Due to the limited payloads available on both Tiers of UAV, the identified selections proved limited. Many of the weapons considered are in early stages of development or notional at this time. For those cases, there was minimal specification or performance data available. During identification of candidates, only the weight of the actual weapon was included. Weights of additional

necessary components, such as mounting hardware or necessary electronic support, were considered separately.

Table 26 - Initially Identified Candidate Weapons

Weapon Name (Country)	Weapon Type	Weapon Weight (pounds)
Unguided Munition (U.S.)	Dumb Bomb [notional]	10
GPS Guided Munition (U.S.)	GPS/SAL Guided Ballistic	6
Selectively Targeted Skeet (U.S.)	EO/IR Cluster Munition	10
Viper Strike (U.S.)	IR Guided Munition	44
M66 (U.S.)	Unguided Missile	30
Explosive Nose Cone (U.S.)	[notional Tier I only]	1.5
Switchblade (U.S.)	EO Guided Missile (UAV)	2.2
SPIKE-NAVAIR (U.S.)	EO Missile	5.3
Precision Guided Mortar Munition (U.S.)	GPS/INS Mortar	10
Stinger (U.S.)	IR Missile	23
SPIKE-MR/LR (ISR)	EO/IR Missile	23.1
Javelin (U.S.)	IR Missile	26
LAHAT (ISR)	SAL Missile	29
Griffin (U.S.)	SAL Missile	33
Scorpion (U.S.)	SAL Guided Glide Munition	34
Advanced Precision Kill Weapon System (U.S.)	SAL Missile	35
DAGR™ (U.S.)	SAL Missile	35
SPIKE-ER (ISR)	EO/IR Missile	73

For both Tiers of UAV, the weight of a weapons management system (WMS) and weapons mounting hardware was considered in weight calculations. The sophistication of the WMS depends on the weapon system, but was expected to include certain minimal electronics processing capabilities necessary for informing the operator of weapon status, processing engagement and dispense requests, and interfacing between the weapon and UAV message bus. The complexity and weight of any required mounting hardware was also weapon specific, and could range from a simple plastic tube dispenser to a complicated missile launch rail or bomb rack.

Guns were not selected as possible candidates on either Tier of UAVs. The Tier I UAV does not have the payload to carry a gun, ammunition, and necessary mounting hardware. Analysis of Tier II target attack scenario susceptibilities indicated that if the UAV was within successful target engagement range using a gun, the UAV was also susceptible to enemy defenses. Accurate aiming of a gun from a Tier II UAV flying on described scenarios could also prove problematic, increasing the possibility of collateral damage. Including a mounting gimbal to enhance weapon accuracy would greatly increase weapon system weight. Finally, the effect delivered to the enemy using a gun was not felt to be sufficient for the required weight of the system.

1. Tier I UAV Weapons

The Tier I UAV presented a significant challenge to incorporate the addition of a weapon capability due to its small available payload of just 2.5 pounds. If a mounting and WMS weight of a total of one pound was assumed, 1.5 pounds was available for weapon use. The only option identified as acceptable, due to weight constraints, was an Explosive Nose Cone.

This option is not a currently available weapon. Instead, it is proposed that a warhead may be fitted inside the replaceable nose cone of the UAV. The UAV would then proceed on a mission to identify and attack a target. The device could have simple impact fusing in addition to a safe-arm system. Necessary interfaces through the weapon controller would be minimal due to the simple functionality of the device. The operator would have a single control arm.

The Explosive Nose Cone was not considered a feasible option at this time. The fitting of an explosive device to the UAV would require some type of safe-arm device to be included as part of the installation for safety in transport. When preparing the vehicle for launch, the safe-arm device would be placed in the arm position, This Tier of UAV is hand launched, resulting in the possibility of its impacting the ground close to the launch personnel and detonating the device.

Instead of modifying existing Tier I UAV for use as guided missiles, it may prove more time and cost effective to seek a commercial off-the-shelf disposable UAV

capability. Such a device is currently in development by AeroVironment and is described in more detail below. As there are no feasible weapon options available for the Tier I, no further analysis will be performed on this vehicle.

2. Tier II UAV Weapons

The Tier II surrogate total available payload of 93 pounds allowed for a much broader selection of weapons. The IAI POP-300D sensor package, considered part of the Tier II surrogate, consumed 35 pounds of the available payload, leaving 58 pounds maximum for weapon systems usage. Estimates of weights for required mounting hardware and support electronics were as follows.

- The weight of the WMS for the Tier II was estimated to be 10 pounds, which included the weight of all associated wiring and housings for the WMS. Team Bravo member James Tuey has supported development of two such WMS intended for use on the surrogate-sized UAVs and felt that 10 pounds was a representative weight. With the weight of the WMS considered, a total of 48 pounds remain available for weapon use.
- The mounting for each non-missile weapon was estimated to be 10 pounds per round. The estimate was based on the seven pound weight of the MA-4 bomb rack and an additional three pounds allowed for adaptor hardware (Fed Biz Ops 2009).
- The mounting of any missile weapon was estimated to weigh the same as the weapon itself. M299 Hellfire missile launchers intended to carry four missiles in current use on U.S. helicopters weigh 145 pounds empty (Lockheed-Martin 2011). However, these racks are intended to survive a more severe environment than that expected for the Tier II UAV. The mounting was also considered to include any launch tube, if required, for the weapon.

a) Unguided Ballistic Munitions

This type of device is commonly referred to as a “dumb bomb.” The munition has no propulsion mechanism and relies on gravity as the delivery force. Lateral translation is due solely to dispensing vehicle velocity prior to dispense. No guidance capability is provided and the weapon trajectory is purely ballistic. The device used in this study was notional. Ideal dispense parameters required to successfully engage the

target using the altitudes and airspeeds specified in the mission scenarios were developed and used in modeling of the scenarios. The effects of aerodynamic drag were included in the calculations, assuming a pointed nose and cylindrical shape. As this was a notional weapon design and not currently known to be in production, no illustration of this type of weapon was available. At an estimated weight of ten pounds each and including the estimated ten pounds per weapon mounting weight, the Tier II UAV could carry two of these devices at takeoff within the available 48 pounds of payload weight.

b) Guided Ballistic Munitions

Two examples of guided ballistic weapons were identified that could be carried within the previously defined weight restrictions of the Tier II vehicle. Both are developmental weapons. Detailed information available in open sources concerning the weapons was not available. Some information concerning sizing, weight, and anticipated weight was obtained and used to develop possible engagement boundaries.

(1) GPS Guided Munition (G2M). This weapon is being developed by ATK. Its planned low weight of approximately six pounds will allow even smaller UAVs to carry multiple rounds. As it is a non-propelled weapon, a majority of the weight is available for use as a warhead. Approximately four pounds of the weapon’s weight is being allocated to warhead. Use of both GPS and semi-active laser guidance allows for precision guidance and reduced collateral damage. Figure 51 displays an illustration of the ATK G2M. Approximate sizing of the device was developed by analysis of drawings illustrating the mounting of the devices on a MQ-5B Hunter UAV (Defense Update 2011). As these are non-missile weapons, the estimated additional mounting weight for each weapon was ten pounds, which includes the seven pound mounting rack and three pounds of hardware for adapting to the Tier II surrogate. Using the anticipated weapon and mounting weights, each weapon round would require sixteen pounds of the 48 available payload pounds. The Tier II UAV could carry up to three of these weapons at takeoff.

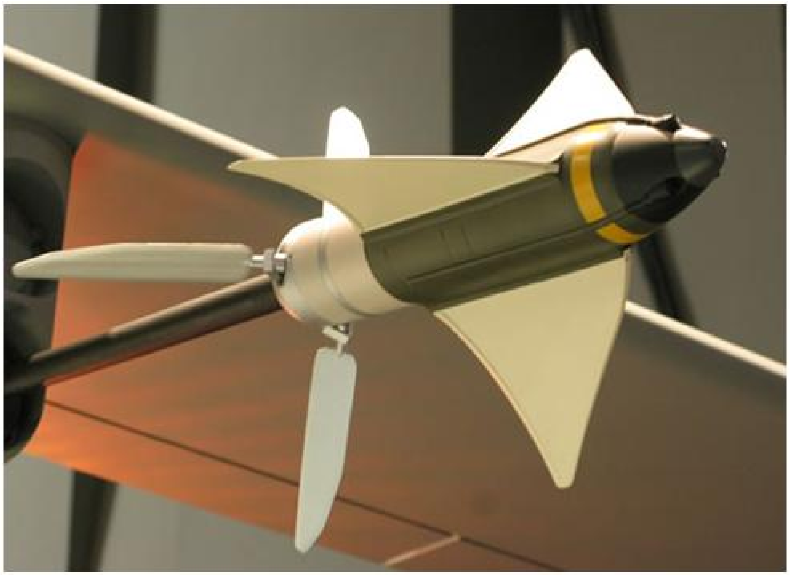


Figure 51 - GPS Guided Munition (G2M) from (Defense Update 2011)

(2) Selectively Targeted Skeet (STS). This weapon is being developed by Tektron Systems as a munition for use in a cluster munition dispenser. Intended for use as an anti-armor weapon, the STS is dispensed over the battle area. An internal rocket motor causes the weapon to spin once deployed. Using a dual-mode active/passive sensor system, the weapon utilizes a deployed Samara wing, similar to a maple seed, to steer to a target. Once in position, its precision explosively formed penetrator (EFP) warhead is fired downward at the target. The near vertical trajectory of the warhead reduces the possibility of collateral damage. If a target is not found within a certain amount of time, the STS will self-destruct. Figure 52 illustrates the STS munition in its deployed configuration (Textron Systems 2011). The STS munition weighs approximately ten pounds. Combined with the estimated ten pounds per round mounting/dispenser weight, each weapon round would require twenty pounds of payload weight. With a maximum of 48 payload pounds available, the Tier II UAV could carry two of the rounds at takeoff.

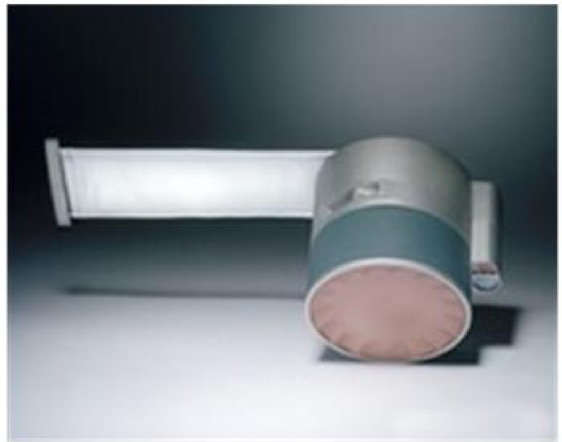


Figure 52 - Selectively Targeted Skeet (STS) (Textron Systems 2011)

c) Unguided Propelled Munitions

The M66 unguided propelled rocket rounds identified during the weapons search were found to be overweight for the Tier II platform and were not considered further. Additionally, lack of guidance capability greatly increases the chance of collateral damage.

d) Guided Propelled Munitions

Though the initial search for possible weapons identified several options, once the weight of the WMS and mounting/launch hardware was included, several of the weapons were found to be overweight and were screened out of further analysis. Two of the remaining weapons are developmental, while three are in current deployment. In all cases, analysis of the weapon characteristics and performances were based on open source literature which may affect its accuracy.

(1) Javelin Anti-Armor Missile. The Javelin system is a fire-and-forget missile system that has been in full rate production since 1997. The full system includes the missile, a launch tube, and the command-launch unit (CLU). The missile itself weighs 26 pounds. Target tracking is accomplished using passive infrared, depending on target lock-on before launch (LOBL) (IHS Global Limited 2010). Figure 53 shows a model of the Javelin missile round.

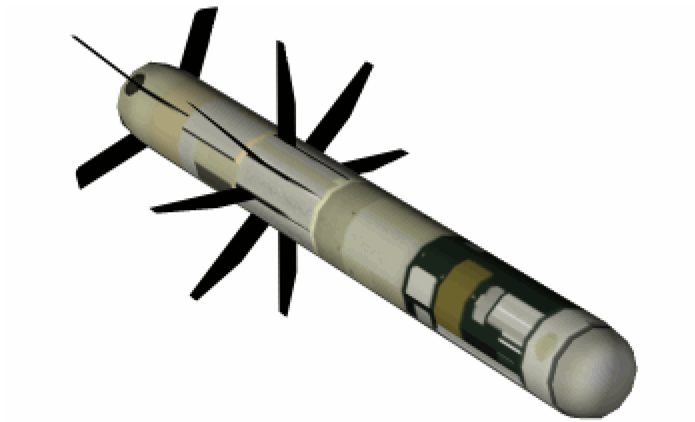


Figure 53 - Javelin Anti-Armor Missile (Grime 2007)

In operation, the operator would detect the target using the CLU. If the decision was made to fire, the weapon would be activated. A choice of trajectory for top attack or direct attack is made prior to launch. At firing, an eject motor propels the round away from the gunner. Once at a safe distance, the main rocket motor fires to propel the missile to the target. No further inputs to the missile from the gunner are required once the missile has been fired, allowing the gunner to either reload or reposition. The current warhead is a two-stage EFP; however, future versions will include a multipurpose warhead that will include both EFP and fragmentation effects. Maximum range of the Block I Javelin missile is given as 2,500 meters (Net Resources International 2011).

The combination of the missile weight of 26 pounds and anticipated mounting/launcher weight of 26 pounds, the total weapon weight was approximately four pounds over the maximum available payload weight of the Tier II UAV of 48 pounds. However, the Javelin missile was retained as an option for further study due to the low weight overage. Given the current weight approximations, the Tier II UAV surrogate might carry a maximum of one Javelin missile.

(2) SPIKE-MR/LR Anti-Armor Missile. These missile systems were originally developed by Rafael for the Israeli Ministry of Defense. The SPIKE-MR is similar in capabilities to the U.S. Javelin anti-armor missile. It operates in fire-and-forget manner similar to the Javelin, using either a passive IR or daytime (EO)

seeker. The SPIKE-LR is an improvement to the MR version and allows for a fiber data link from the operator CLU to the missile to send commands during flight. The missile operates in a LOBL mode only (IHS Global Limited 2010). Figure 54 depicts a SPIKE-MR/LR missile round.

Figure 54 - SPIKE-MR/LR Missile (Defense Industry Daily 2008)

The SPIKE system also has a two-part propulsion system to first propel the weapon away from the launcher before igniting the main rocket motor. It has a multipurpose warhead and a choice of trajectories for use in engaging different target types. Its maximum range is given as 2,500 meters (EuroSpike GmbH Unknown).

The combination of the SPIKE-MR missile weight, anticipated mounting/launcher, and WMS was found to be slightly under the maximum available payload weight of the Tier II UAV. Given the current weight approximations of 23.1 pounds for the weapon and 23.1 pounds for mounting/launching hardware, the Tier II surrogate UAV could carry a maximum of one SPIKE-ER missile at takeoff.

(3) Stinger Anti-Air Missile System (FIM-92). The current version of the Stinger system has been in production since 1992. The missile was designed for surface-to-air use against a variety of rotary and fixed wing targets, and improvements have been made through the years to enhance its capabilities against cruise missiles as well as to allow its use as an air-to-air missile. The design of the missile system includes the capability of operational software reprogramming in the field without disassembly. The

missile itself weighs approximately 23 pounds and is equipped with an impact-fused fragmentation warhead (IHS Global Limited 2010). Figure 55 shows the Stinger missile system including detachable eject motor.

Figure 55 - Stinger Anti-Air Missile System (Raytheon n.d.)

In typical operation, a gunner would power the weapon system, and aim at the target using optical mechanisms on the reusable launcher electronics. The Stinger uses a dual band pseudo-imaging detection system to track the target in a variety of situations. Once the target has been sighted, the WMS allows the missile to track the target. Successful target lock is indicated by tone. The missile is then fired. A separable eject motor propels the missile from the tube to a safe distance in front of the launcher. The two-stage motor is then fired, and the missile rapidly accelerates to over Mach 2. The missile is guided using proportional navigation law to intercept the target's flight path. Shortly before impact, the aimpoint of the missile velocity vector is shifted away from the target's engine, causing the missile to impact the target body. The maximum range of the Stinger missile is estimated to be 4.5 kilometers (IHS Global Limited 2010).

The Stinger system has been demonstrated by the Army for air-to-air use from a helicopter. At the expected combined missile weight of 23 pounds and mounting/launcher hardware weights of 23 pounds, the Tier II UAV can carry a single Stinger round and remain within the available payload weight of 48 pounds.

(4) NAVAIR Spike Missile System. The NAVAIR Spike missile system has been called the world's smallest guided missile system. Currently in development by a joint government-industry team, the missile was originally envisioned as a small man-portable precision fire-and-forget missile system for use against asymmetric targets. Early successes have expanded its possible role to use on UAV platforms. The missile itself is 2.25 inches in diameter, 25 inches long, and weighs approximately 5.3

pounds, with a one pound EFP warhead for reducing collateral damage. It can be launched from either a reusable shoulder launcher or remotely from a vehicle launcher (Felix 2006). Figure 56 illustrates a cutaway of the NAVAIR Spike missile.

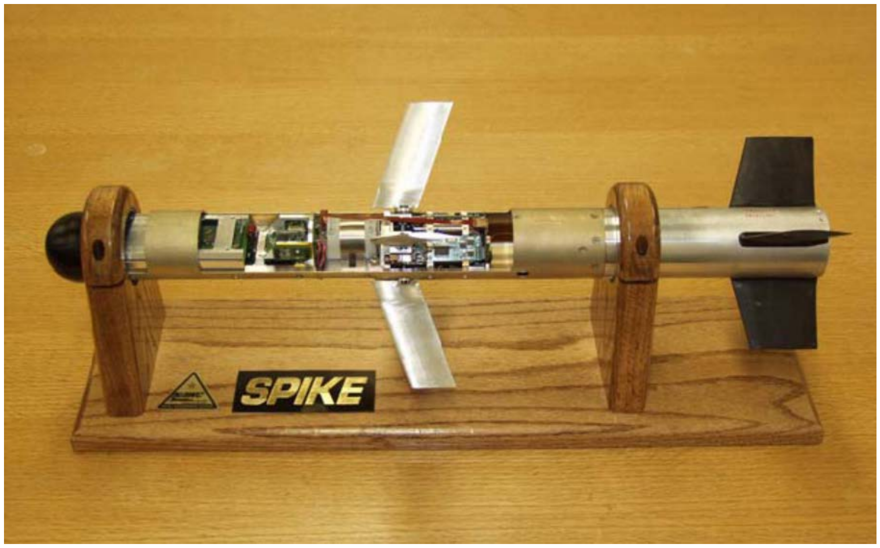


Figure 56 - NAVAIR Spike Missile (Felix 2006)

The operation of the missile is anticipated to be similar to other LOBL systems. The gunner will perform the task of verifying target acquisition as in other systems. Once the gunner has verified the target, the missile would be launched. The small rocket motor would accelerate the missile to its maximum speed of an estimated 800 feet per second. Target detection and guidance is provided using a COTS focal plane array operating in the visual band, though both IR and SAL options are being investigated. Designed for low cost, the system uses a non-gimbaled detector system, limiting the engagement capability of the system to slower moving targets. A contact-only fuse will detonate the warhead on target impact. The NAVAIR Spike missile has demonstrated engagement ranges of over 1.5 miles (Felix 2006).

The NAVAIR Spike has been demonstrated against a variety of fixed, moving targets. Given the low weight of the Spike missile system of 5.3 pounds each and anticipated lower weights of mounting/launcher hardware of 5.3 pounds per

round, the Tier II UAV could carry up to four rounds and remain within the 48 available payload pounds.

(5) Switchblade Agile Munitions System. The Switchblade is a developmental project of AeroVironment. The battery-powered vehicle is designed to be flown by an operator using feedback from an on-board EO sensor. An IR sensor-equipped version is being developed and is anticipated to become available soon. It is being designed as a disposable system (Defense Update 2004-2009). Figure 57 illustrates anticipated Switchblade appearance.

Figure 57 - Switchblade Mini-UAV (AeroVironment, Inc. 2011)

Called by AeroVironment "Man-portable ISR with Teeth," the Switchblade is planned to provide both ISR capabilities as well as precision munition in one lightweight and portable package. The vehicle may be launched by hand, from a launch tube, or from air vehicles such as UAVs. Miniaturized avionics and sensors provide information to the operator using a portable control station. If desired, a small lethal payload may be carried by the vehicle and terminal guidance provided by an onboard video tracker system, allowing for precision strike with low collateral damage (Grabowsky 2007). The range of the system is unknown at this time, but is anticipated to be between twenty and forty kilometers (Strategy Page 2010). Each Switchblade is expected to weigh 2.2 pounds. Allowing for necessary mounting hardware, the Tier II UAV could carry up to ten of these weapons.

3. Feasibility Screening and Remaining Weapon Candidates

Identified weapon possibilities were screened to limit to those feasible for the RUINS implementation. To reduce the possibility of collateral damage, unguided propelled munitions were screened out. Guns were removed from further consideration for two primary reasons. First, the effective range of the weapon would force the UAV into enemy defense range during engagements, and second, the amount of effect a gun can deliver to the enemy was felt small in comparison to its weight. Weight was a primary screening criteria. Due to the limitations on weapons options and operator safety concerns, the Tier I UAV has been screened from further investigation. More options were available for the Tier II due to the increased available weapon payload of 48 pounds. These include a simple bomb, guided ballistic weapons, and several guided missiles. One additional weapon was screened from the Tier II candidate list for reasons other than weight. The Precision Guided Mortar Munition (PGMM) is a mortar round. Its expected flight trajectory is based on that of a mortar: it is fired from a mortar and propelled to high elevations, where it begins scanning for a target. If one is found, it then guides and attacks (Burke 2004). This trajectory was not felt feasible for the UAV use, though future versions of the PGMM are intended to be fired from a 120mm gun. Though several weapon options for the Tier II were initially identified, screening decreased the number of candidates for continued investigation to eight.

Though the initial identification of possible weapons identified several available and developmental weapons by specific name, the weapons used in the study are all surrogates developed from open source documents and engineering approximations. The results of any modeling performed using the surrogates should not be considered indicative in any way of the performance of the actual systems. To prevent the unintentional correlation with an existing system, the surrogate systems were code named for the remainder of the project. Table 27 provides an approximate crosswalk between the surrogate and the actual weapons. The Tier II candidates considered for further investigation are listed in Table 28.

Table 27 - Surrogate Weapon Crosswalk

Surrogate Weapon Name	Identifier	Weapon Emulated
Bomb	B or Bomb	Dumb Bomb
Guided Bomb 1	GB-1	GSM
Guided Bomb 2	GB-2	STS
Missile 1	M-1	Javelin
Missile 2	M-2	Spike-MR
Missile 3	M-3	Stinger
Missile 4	M-4	Spike-NAVAIR
Missile 5	M-5	Switchblade

Table 28 - Screened Tier II Candidate Weapons

Weapon	Type	Available Payload (lbs)	Weapon Weight (lbs)	Mounting (each) (lbs)	Maximum Rounds
Bomb	Unguided Ballistic		10	10	2
GB-1	Guided Ballistic		6	10	3
GB-2	Guided Ballistic		10	10	2
M-1	Guided Propelled	48	26	26	1
M-2	Guided Propelled		23.1	23.1	1
M-3	Guided Propelled		23	23	1
M-4	Guided Propelled		5.3	5.3	4
M-5	Guided Propelled		2.2	2.2	10

F. Logistics Analysis

1. Acquisition Logistics

The RUINS concept was based on taking general specifications for already fielded UAS and combining them with fielded or in-development weapons systems. The result is applied directly to existing systems. Procedures for weapons handling, takeoff and landing, and maintenance will have to be developed.

2. Operational UAV Logistics

The UAS is composed of many parts including the air vehicle (UAV) and the ground or portable control station. While much simpler than a manned vehicle system and although the consequence of its loss is much less, preventing failure of the UAS is important in supporting both the RUINS and existing ISR missions. “The current UAV

accident rate (the rate at which the aircraft are lost or damaged) is 100 times that of manned aircraft" (Bone and Bolkcom 2003). Maintenance is important to the UAV.

There are two forms of maintenance that can be performed: preventive maintenance and corrective maintenance. According to the definitions developed by Global Security, "Preventive maintenance consists of preflight and post flight inspections, and routine servicing including pre-launch and post-launch inspections, acceptance inspection and initial buildup, corrosion control and preservation. Corrective maintenance involves minor structural repair as well as fault isolation and access, removal, and repair or replacement of failed components to the lowest level replaceable assembly" (Global Security 1999). Both are critical to keeping the system operational and in the field. Since its tasking includes identifying IEDs that have been planted, identifying persons planting the IED, as well as normal ISR operations, UAS availability is crucial. Any part of the system that is not functioning properly could cause a complete UAS malfunction, and potentially mean loss of life to either Coalition Forces or civilians. It is crucial to perform preoperational tests to verify the system is ready to operate using built in tests as well as manual inspections (Global Security 1999). This allows the users to verify there are no equipment function obstacles that will prohibit the UAV from successfully performing its mission. Though preventive maintenance and pre-operational tests are widely used, not all problems can be prevented from occurring. When problems do occur, fault detection and isolation help pinpoint its source and functional tests verify its resolution (U.S. Army 1995). Since maintenance factors were involved in 2–17 percent of the reported accidents depending on the type of UAV, it is important that maintenance is completed correctly and by trained personnel (Alan Hobbs 2006).

A study of U.S. Army UAV accidents determined that 32 percent of accidents involved human error, whereas 45 percent involved materiel failure either alone or in combination with other factors (Alan Hobbs 2006). This indicates proper training is necessary to maintain system reliability. "Several operators reported that UAVs were delivered with operating manuals, but without a maintenance manual or maintenance checklist. As a result, the operators developed their own maintenance procedures and documentation. Other UAV operators reported that their UAVs were delivered without

technical information such as wiring diagrams, making it difficult to troubleshoot problems or repair electrical systems" (Alan Hobbs 2006). Improper training and not having the right tools to accomplish the maintenance could mean an increase in mean time to repair (MTTR) and a lower mean time between failures (MTBF), which results in less time for the UAV to be operational. The RUINS concept intends that the addition of a weapons system will not overly impact the maintenance mission. However, the inclusion of any additional equipment and capabilities will increase the maintenance requirements. Weapons system support will be in addition to the current Tier I and Tier II maintenance and support concepts. Spares and repair equipment for the mounting hardware will be added to the basic UAS unit. It is believed that the existing weapons supply chain will be able to support addition of the UAV weapon without severe impact. Yet specially trained weapons personnel and associated equipment will be required on the maintenance team. The number of additional personnel and equipment requirements are weapon-specific, and will be better determined once a final weapon solution is selected.

3. Post Operation Actions

Post operations (post-ops) are just as important as the operations itself. Post-ops allow the forces to analyze what has happened, what went wrong and what can be improved for the next mission. Post-ops may vary depending on the outcome of the mission. The RUINS concept would assist in the missions for the three scenarios discussed below. These include: 1) If the IED was located and neutralized 2) If the IED was/was not located, detonated and inflicted harm or caused damage, and 3) if a person was captured planting the IED or trying to detonate the IED.

The main activities in C-IED are: attack the network, defeat the device, and train the force. These parts include, but are not limited to, lethal and non-lethal actions against the network, detection, mitigation and neutralization of IEDs, and training the force to stay ahead of the adaptive enemy (Oates 2010). All post-operations are imperative to getting ahead in the fight against IEDs, commonly referred to as getting "left of the boom." There is something to take away or learn from each scenario/operation to allow the forces to protect themselves and stay ahead of the enemy.

G. Summary

The existing UAVs and their supporting systems and activities were examined to better identify operational limitations and opportunities. Further investigation into possible performance of the planned scenarios was performed to better understand issues of enemy defenses and possibilities of damage to the UAV. A wide variety of candidate weapons that might be applicable to the RUINS project were identified, along with their strengths and weaknesses. A list of candidate weapons was obtained by performing open-source research, and was further screened for applicability to the RUINS effort. An analysis of risks involved with the RUINS project, and their mitigations, were presented.

The result of the analysis contained in the chapter was a specific list of candidate weapons that might satisfy the sponsor needs. The small available payload and operator safety concerns led to the screening out of the Tier I platform from further weaponization investigation. Due to Tier II UAV's larger available payload, several possible weapons were identified for continuing analysis. The candidates weapons identified include a simple unguided ballistic bomb, two types of guided ballistic bombs, four different types of rocket propelled guided weapons, and one propeller-driven guided weapon. The guidance methods include GPS, semi-active laser, infrared, and electro-optic. The diversity of identified candidates offers a broad spectrum of implementation options. These candidates will be further investigated in the next phase of the process, Analysis of Alternatives.

IV. Analysis of Alternatives

The candidate weapons identified during the Design and Analysis phase offered different delivery, guidance, and warhead options. Many considerations were made during the analysis, and several possible weapons were screened out as a result of this investigation. To further assess the strengths and weaknesses of each of the identified candidates in an operational scenario, additional modeling methods were used.

Four major types of modeling were performed during the Performance Analysis. The surrogate weapons were modeled and utilized in an operational environment simulation designed to closely emulate the representative scenarios developed during the Problem Definition phase. Technical performance measures were gathered during the modeling and used for assessing relative performance. Additional modeling was performed separately to assess the destructive abilities of candidate warhead technologies and the aerodynamic effects of adding weapons to the UAV. A financial analysis was also performed to assess the life cycle costs of the various possible solutions. Finally, the results of the modeling and financial studies were integrated to assist in the identification of the optimum solution for the RUINS. The details of the modeling and simulation and analysis efforts are presented below.

A. Performance Modeling and Simulation

Modeling and simulation tools provided the mechanism to evaluate candidate UAS solutions to accomplish RUINS objectives. The Systems Engineering Analysis of Alternatives (AoA), cost and performance trades were performed by the application of statistical methods to modeling and simulation results.

1. Modeling and Simulation Tools

Several modeling and simulation tools were evaluated during the early phases of the RUINS project. Availability, capability and suitability were key factors in determining the appropriate modeling and simulation tool set for the RUINS project. Figure 58 provides an overview of the modeling and simulation environment.

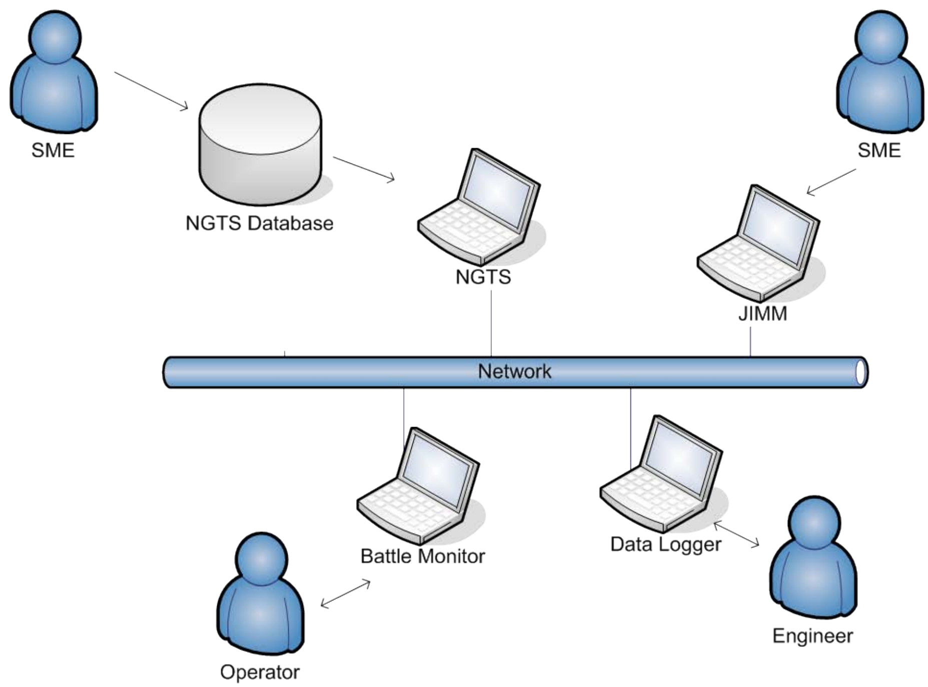


Figure 58 - RUINS Modeling and Simulation Environment

The Joint Integration Mission Model (JIMM) and Next Generation Threat System (NGTS) are constructive threat and mission models developed and maintained by the U.S. Government Department of Defense (DoD). JIMM is currently used jointly by the U.S. Navy and Air Force for live, virtual and constructive testing and training. NGTS is a computer generated forces (CGF) threat simulation used for U.S. Navy and Air Force Fleet synthetic, live, virtual, and constructive training and exercises. NGTS uses a parametric database to supply inputs to the model. Subject Matter Experts (SMEs) in the areas of Electronic Warfare (EW) and weapon systems are required to populate data for the parametric database. The software simulated NGTS sensor, platform, weapon, communication and environment models use the inputs from the database during execution to simulate a battlespace environment. JIMM simulates a battlespace environment by combining scripts and parameter data to achieve a desired effect. The Battle Monitor provides a graphical user interface to visualize and manipulate simulation during

execution. Interoperability in a distributed simulation environment is accomplished using standards and protocols. The U.S. Air Force uses Simulation International Standards Organization (SISO), Distributed Interactive Simulation (DIS) Standards. The Naval Aviation Simulation Master Plan (NASMP) High Level Architecture (HLA) is used by the US Navy. Simulation data is transported over the network and a GOTS data logger was used to record simulation data. MS Excel and Oracle Crystal Ball were used to manipulate and analyze logged simulation data.

During the evaluation of M&S tools it was determined that JIMM was the preferred tool for the RUINS M&S effort. JIMM supported effects-based-modeling, which simplified the M&S process. Digging for unclassified information on candidate weapon systems for emulated real world simulation systems was an onerous task. Due to availability issues, NGTS was used to perform the final RUINS M&S. The NGTS parametric database drove the need to have "good" but not "real" data on candidate weapons for the models to work correctly, and in some cases, the data to support the necessary weapon system attributes were contrived using engineering judgment. The diverse engineering background of the team became an invaluable asset as several members were weapon, sensor and pseudo aerodynamic SMEs.

NGTS simulation trials were deterministic and only needed to be conducted once as they were repeatable given the same set of input conditions. NGTS supported both autonomous and manual fire modes and both were used during RUINS M&S. During the simulation trials, if the weapon was unable to produce a kill in auto-engagement mode, the trial was rerun and manual fire was used to produce a kill. The model supports a manual sensor mode that provides the ability to manually transition and hold sensors at a given mode and to identify a sensor Target of Interest (TOI). During the Fixed target simulation trials at the 500 foot altitude, this feature was used to allow the longer range missiles to get a kill without a valid visual identification of the target.

2. Design of Experiments (DOE)

Design of Experiments was applied to orchestrate RUINS scenarios to capture key system attributes during M&S. Two target sets, fixed and moving, are defined in two operational environments – urban and rural. Two variations of altitude and one speed were used in the scenarios. The eight surrogate weapons identified as possible payloads for the Tier II UAS were modeled for use in the scenarios. The total number of combinations simulated for a full factorial design as a function of speed, altitude, target and weapons, are defined by 1 x 2 x 2 x 8 = 32.

3. Performance Modeling and Simulation Description

A functional flow of RUINS modeling and simulation is represented in the IDEF0 drawing of Figure 59.

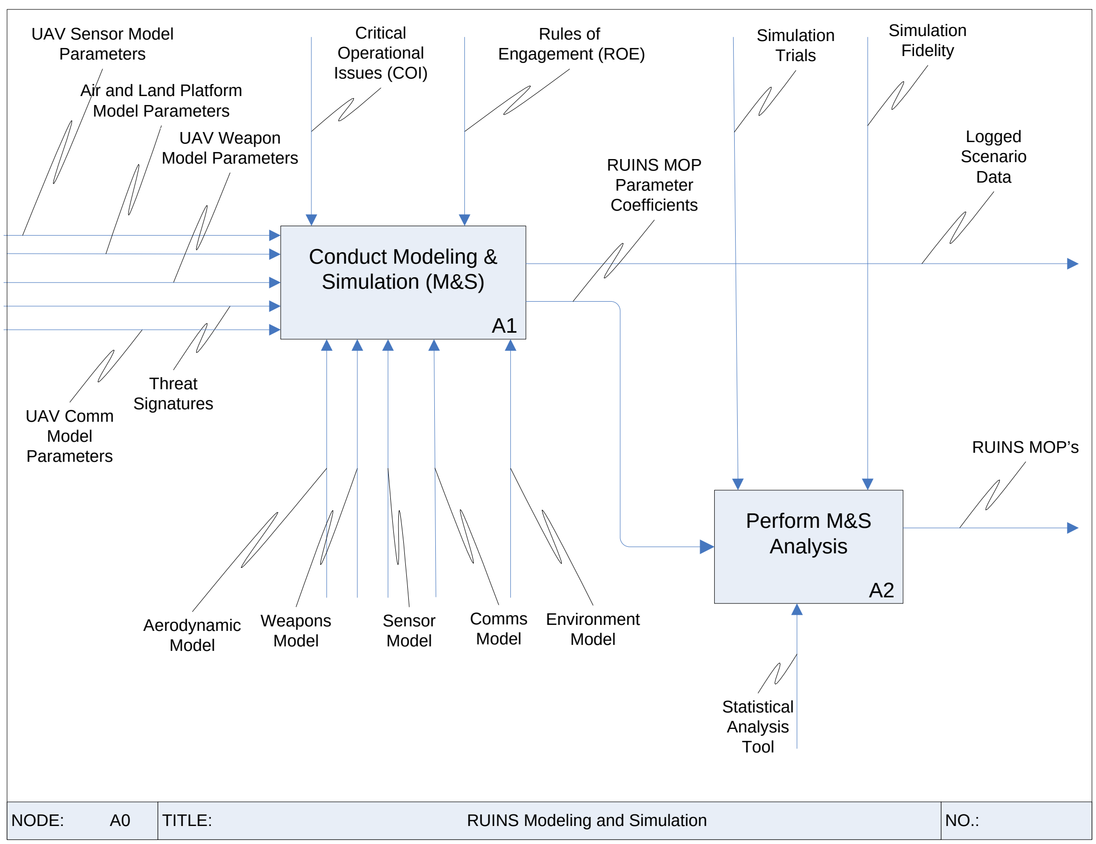


Figure 59 - Modeling and Simulation IDEF0

Parametric data for Tier II platforms, sensors, weapons, communications and threat signatures were inputs to model for simulation. Government owned DoD models were used as the mechanism to employ weapon systems in a synthetic operational environment. Rules of engagement and critical operational parameters provided the control for the simulation execution. Simulation output data was input to the M&S analysis and stored for reference and accountability. Statistical analysis tools were used to facilitate an evaluation of MOP parameter coefficients. The output of the analysis was used as an input to the RUINS Analysis of Alternatives.

a) Model Inputs and Assumptions

Model inputs for the simulation experiments were derived from the systems engineering analysis. RUINS Data was mapped to the NGTS model using a parametric database. The following paragraphs summarize the inputs to the NGTS database.

Model data associated with platforms such as the UAV, life-form, ground control station (GCS) and vehicles were represented by database parameters. The aerodynamic model inputs are described in Table 30. The fixed target, a human with an IED and neutral human bystanders were represented as life-forms with a very small IR cross sectional area. The moving target and neutral vehicles assumed the characteristics of a standard Toyota light-duty pickup truck with a small IR cross sectional area. The GCS assumed the characteristics of a communications radio station.

The electro-optical sensors used in the simulation are defined by the model as sensors. Relevant parameters and values associated with the RUINS Tier II electro-optical sensors are provided in Table 31. The system engineering analysis provided specifications for Tier II optical systems in the spectral bands of 3–5 and 0.4 um to 0.8um range. The optical sensors modeled for the experiments used the specifications provided in the 3–5 range. The scan elevation and azimuth were derived from the RUINS optical FOV and resolution specifications using the relationship (1/ (HIFOV = FOV / Horizontal Resolution and VIFOV = FOV / Vertical Resolution). The scan period is derived from the equation 360 / (Azimuth Scan Rate). The NGTS database scope limit parameter was mapped to the RUINS optical specifications for target size and the detection

range. The following analogies can be made in mapping M&S sensor modes to RUINS optical performance:

Table 29 - M&S Analogies

M&S Sensor Mode	RUINS Optical Performance Parameter
Search	Detection
Track	Recognition
Fire	Identification

The weapon payloads used in the simulation were defined by the model as Weapons. Weapons parameters and values associated with the RUINS Tier I and II weapons are provided in Table 32. The weapons guidance types are Line of Sight (LOS), IR, and GPS/SAL. IR guidance directed the weapon to the target by pursuing the target IR signature, GPS/SAL directed the weapon to the target by calculation of positional data relative to the intended target, and LOS guided the weapon to a target along a continuously updated LOS transmitted to the weapon by the launch platform. Command Guidance for the EO only occurs during the first 10 percent of the weapon time of flight. Flight Profiles were defined by the weapon model as Three Point, Pure Pursuit or Ballistic. Three Point profiles guide the weapon on the line of sight between the shooter and target. Pure Pursuit guides the weapon to the target along a direct line of sight from the weapon to the target. Ballistic flight profiles follow ballistic paths determined by the starting position of the weapon and the initial application of energy. Ballistic rockets follow a semi-ballistic path determined by the starting position of the weapon and the period during which momentum is applied. All weapons modeled used a Probability of Kill (P_K) of 0.7.

Table 30 - Aerodynamic Input Data for Tier II Systems

Platform	Max MACH	Max Load Factor	Min Load Factor	Max Dynamic Pressure (lbf/ft^2)	Max Roll Rate (r/s)	CLMAX	Max Altitude (ft)	Dry Weight (lb)	Wing Area (ft^2)	Wing Span (ft)
Tier II	0.3	1.5	0.5	40.0	0.35	1.6	16,000	370	41.41	22.4

Table 31 - Modeling Sensor Input Data for Tier II Systems

Attribute	Optical Emitter											
	Tier I Fixed Target			Tier I Moving Target			Tier II Fixed Target			Tier II Moving Target		
	Search	Track	Fire	Search	Track	Fire	Search	Track	Fire	Search	Track	Fire
Free Space Det. Range (NM)	3	3	3	3	3	3	5	5	5	5	5	5
Max Azimuth (deg)	180	180	180	180	180	180	180	180	180	180	180	180
Min Azimuth (deg)	-180	-180	-180	-180	-180	-180	-180	-180	-180	-180	-180	-180
Max Elevation (degrees)	90	90	90	90	90	90	90	90	90	90	90	90
Scan Type	SHR	SHR	SHR	SHR	SHR	SHR	SHR	SHR	Circular	SHR	SHR	Circular
Scan Width Elevation (s)	48	48	48	48	48	48	68	68	0	68	68	0
Scan Width Azimuth (deg)	64	64	64	64	64	64	91	91	360	91	91	360
Power (kWatts)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Scope Limit (NM)	0.6	0.17	0.1	2.44	0.61	0.35	6.99	1.75	1	24.48	6.12	3.5

Table 32 - Modeling Weapon Input Data Parameters for Tier II Systems

Attribute	Weapon Name							
	Bomb	GB-1	GB-2	M-1	M-2	M-3	M-4	M-5
Propulsion	Bomb	Gravity	Gravity	Rocket	Rocket	Rocket	Rocket	Prop
EO/IR Guidance	Unguided	GPS/SAL	IR	Unguided	EO/IR	EO/IR	EO-LOS	Unguided
Flight Profile	Ballistic	Pursuit	Pursuit	Ballistic	Pursuit	Pursuit	3- Point	Ballistic
Mass (slugs)	0.3108	0.186	0.3108	0.808	0.717	0.714	0.164	0.0683
CCA (sq ft)	1	0.1875	0.208	1.479	1.2	1.1	0.39	0.011
Cd	n/a	0.002	0.0028	0.002	0.003	0.004	0.002	0.02
Sustain Time (s)	1	5	2	2	5	5	3	5
Sustain Mdot (slugs/s)	0	0.02	0.02	0.02	0.0513	0.0513	0.02	0.0072
Sustain ISP (s)	0	150	250	250	100	130	180	150
Az Gimbal Limit (deg)	N/A	180	180	30	30	30	0	0
El Gimbal Limit (deg)	N/A	90	90	30	30	30	0	0
Seeker FOV (deg)	N/A	5	5	2	20	20	30	30
Max Angle of Attack (deg)	0	30	30	30	30	30	30	30
Min Slant Range (ft)	0	200	200	500	200	500	200	200
Max Slant Range (ft)	2,000	3,000	6,000	1,000	10,000	15,000	2,500	7,500
Max Engage TOF (s)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
LOBL	No	No	No	No	Yes	Yes	No	No

Platforms, sensors and weapons were combined to create a Weapon System or UAS. Sensors defined in Table 29 are applied to Tier II platforms to create a representative fixed and moving target UAS. Weapons defined in Table 30 are mounted to the center of gravity of the UAV to create a lethal weapon system.

The environment for the scenario included urban and rural settings. The Tactical Area was defined as NE(N40,W113) SW(N31,W120), which is located in the South West U.S. Region. Cultural features, such as buildings, were occulted during the simulation. Wind Tables derived from China Lake historical weather data and Standard Day atmosphere were input to the weather model. One, two and three story buildings were modeled as cultural features and had dimensions described in Table 33.

Table 33 - Simulated Building Dimensions

Building	Length (ft)	Width (ft)	Height (ft)
1 Story	50	260	10
2 Story	150	175	20
3 Story	350	150	30

Weapon systems, environment, cultural features, routes and waypoints were combined to construct a scenario. The fixed target scenario for the Tier II systems is shown in Figure 60.

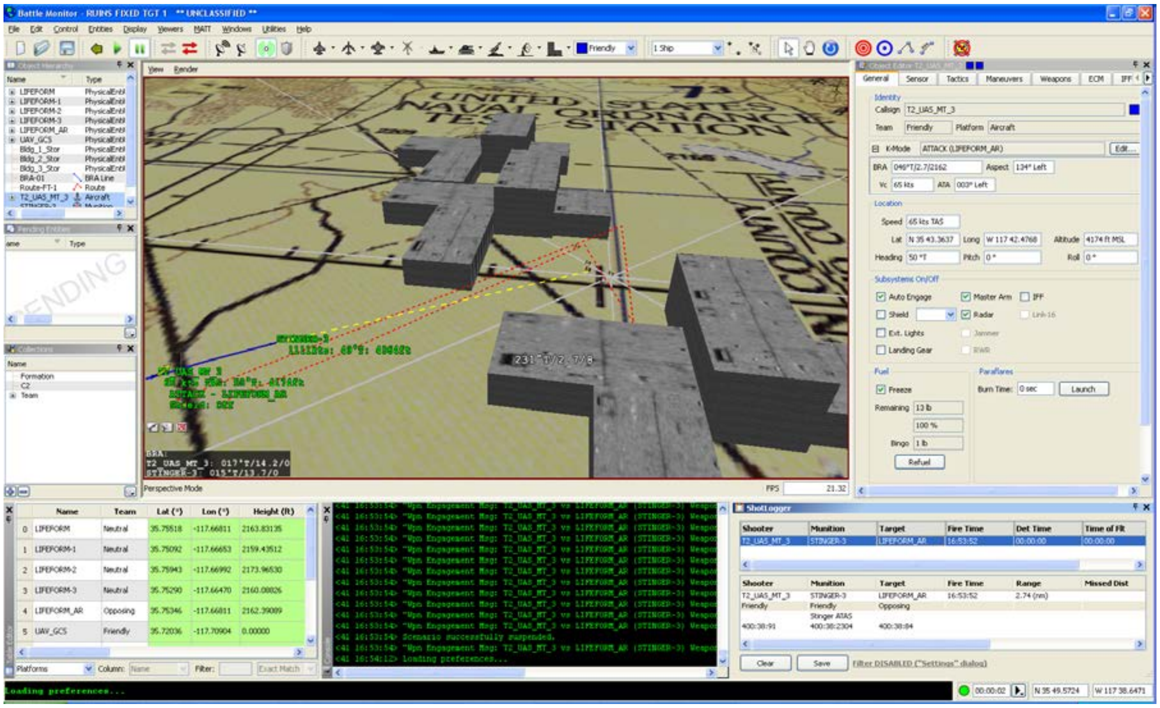


Figure 60 - Battle Monitor Graphic of Fixed Target Scenario

During execution of the fixed target scenario, the UAS is launched from the GCS west of the target and flies a route slightly north of the target. The UAS flies a short distance south, turns northward and eastward to engage the target, and then flies a route back to the GCS. Friendly and neutral personnel are at a distance of 10, 20 and 30 feet from the target.

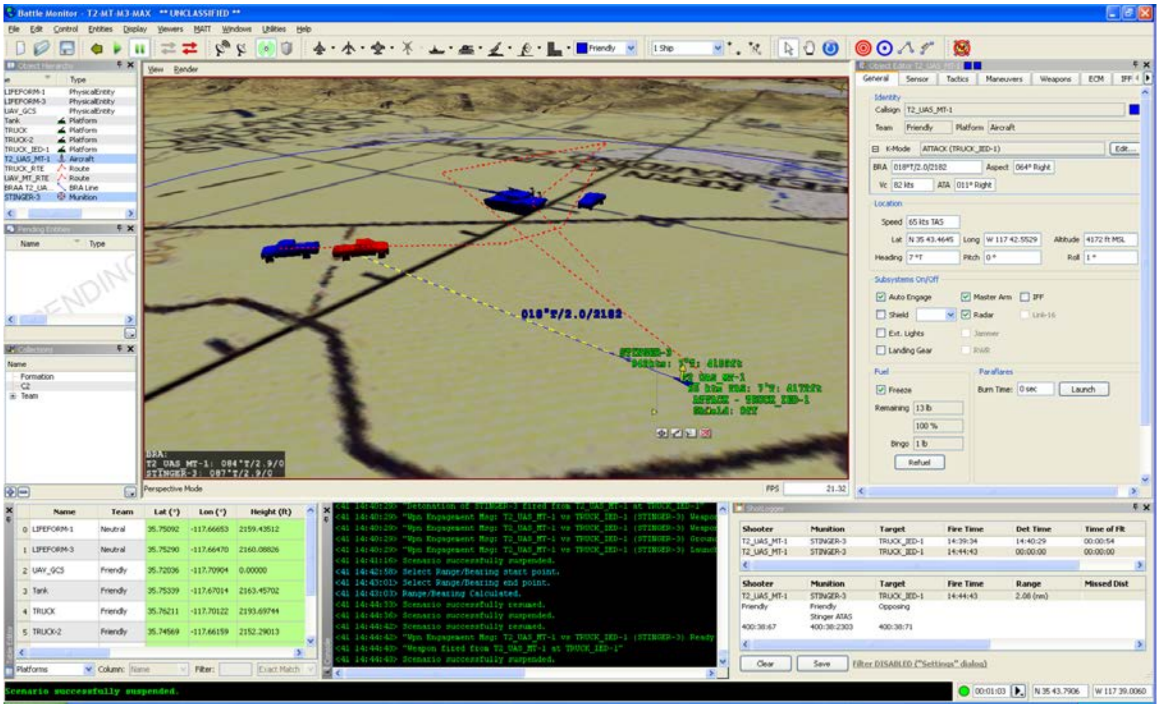


Figure 61 - Battle Monitor Graphic of Moving Target Scenario

During execution of the moving target scenario, the UAS is launched at a distance of 2.5 nautical miles (NM) south of the target at a heading of 50˚ T. The target is a light duty pickup truck heading 135˚ T at a speed of 40 knots (kts). There is a combination of neutral and friendly vehicles and personnel along the route and in the vicinity. The UAS sensor begins in search mode the UAS and flies along a surveillance route until it comes within the track scope limit of the target. The sensor transitions to track mode and performs a fly-to-target tactic. As the UAS converges on the target, the sensor transitions to fire mode and enables the weapon master arm.

b) Assumptions

The M&S assumed the models used provided sufficient fidelity at an unclassified level to accurately represent a candidate RUINS solution set. The NGTS offline database limited the parameters available for input into the model and assumed a correct correlation was made from candidate RUINS attribute specifications to NGTS database parameters.

In addition to the general assumption that the model was correct and accurate, the following assumptions about the scenarios were made:

- The human target was positively identified as a foe prior to mission execution,
- There was a clear Line of Sight from the Ground Control Station (GCS) to the UAS.
- UAV tactics assumed optical sensor detection ranges met specification.
- The GCS has a positive identification of the target when the sensor model transitions from track to fire.
- Weapons, platform and sensor data were represented at an unclassified security level.

c) Constraints

The following list of constraints bounded the modeling scenarios:

- Aerodynamic glide as a UAV counter to audio detection by adversaries was not modeled.
- Time of Day (TOD) was modeled as a fixed percentage reduction in visibility
- Communication links were not blocked by terrain or other objects.
- The communication datalink was either present or not.

4. Performance Modeling and Simulation Results

The numerical results of the M&S effort are summarized in Appendix D of this document. The data in Table D-1 and D-2 provide a summary of weapon engagements from the logged data. The headings in the tables can be deciphered as follows:

- Shooter – weapon system that launched the weapon
- Time of Flight – total weapon time of flight in seconds
- Detonation Result – one of the enumerated values identified in the table below.

Table 34 - Detonation Result Values

Field Value	Detonation Result
1	Entity Impact
2	Entity Proximate Detonation
3	Ground Impact
4	Ground Proximate Detonation
5	Detonation
6	None or No Detonation (Dud)

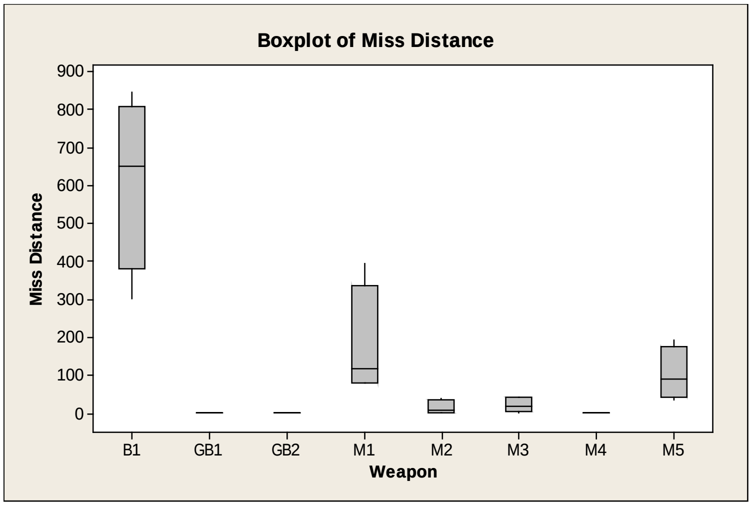
- Shooter to Target Range – slant range from the shooter to the target when the weapon is fired
- Target Miss Distance – distance of the weapon from the target when it detonates
- Quantity Hit – 1 indicated the target is impacted by the weapon during detonation and 0 indicates it is not impacted
- Score – 1 if the weapon detonation resulted in enough damage to kill the target and a 0 if the target is not killed as a result of the detonation

One goal of the simulation exercise was to determine the maximum range that the target could be engaged with a denotation result of 1 – “Entity Impact” or 2 – “Entity Proximate Detonation.” To accomplish this, the UAV performed an auto-engagement against the target and if it did not produce a result of 1 or 2, the weapon fire input parameters were adjusted and the simulation trial was rerun. During these trials, it was observed that a maximum range to target could be found where the values for miss distance, time of flight and range to target had less than a one percent deviation. In the case where an optimum range to target with a detonation result of 1 or 2 could not be found with the auto-engagement, the targets were engaged manually. Weapons B1, M-1 and M-5 were engaged manually using the Battle Monitor weapon fire button. During these simulation trials, weapons were fired and the value of miss distance, range to target, and time of flight were recorded when the weapon fire produced a detonation value of 2. It was observed during manual engagements, that the value of miss distance and range to

target deviated greater than one percent. The statistical average of thirty simulation trials was used to produce a single value for the miss distance and range to target and the results have been summarized in Appendix D. As a measure of performance, the greater the distance from the shooter to target the better, and the smaller the value of miss distance of the weapon detonation to the target the better. A value of 1 for the quantity hit is better than 0 and a value of 1 for the score is better than 0.

The team tested the results for normality. Since the results did not fit a normal distribution, non-parametric statistics are used to evaluate the interactions of the factors: weapon, altitude and target type to miss distance and fire range. The results of the Kruskal-Wallis Test were used to determine the significance of the data means. The test statistic H is compared to $X^2_{(a,n-1)}$ and if H is greater than the critical chi-square value, the hypothesis that there is no difference in medians is rejected. The null hypothesis H_0: the population medians are all equal or H_1, the medians are not all equal, are used to evaluate the data below.

The results of the Kruskal-Wallis Test for miss distance vs. weapons are shown in Figure 62. From the results, weapon M-3 differed least from the mean rank for all observations, Bomb had the highest rank, GB-1 the lowest. In this case the null hypothesis, H_0, was rejected and the alternative hypothesis, H_1, was accepted, which implies the choice of weapon is a statistically significant factor on the results observed for miss distance.



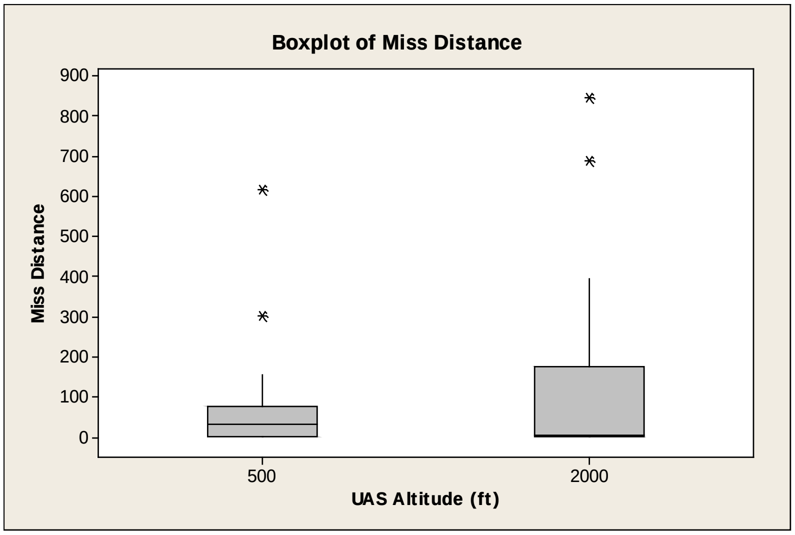
Kruskal-Wallis Test on Miss Distance

Weapon	N	Median	Ave Rank	Z
Bomb	4	651.640	30.3	3.13
GB1	4	0.400	7.5	-2.05
GB2	4	0.390	8.5	-1.82
M1	4	117.985	25.5	2.05
M2	4	8.670	11.8	-1.08
M3	4	18.225	17.5	0.23
M4	4	0.455	7.8	-1.99
M5	4	90.965	23.3	1.54
Overall	32		16.5	

H = 25.49   DF = 7   P = 0.001

Figure 62 - Kruskal-Wallis Test: Miss Distance versus Weapon

The results of the Kruskal-Wallis Test for miss distance vs. altitude are shown in Figure 63. In this case the null hypothesis failed to be rejected, therefore the null hypothesis was accepted which implies altitude is not a statistically significant factor on the results observed for miss distance.



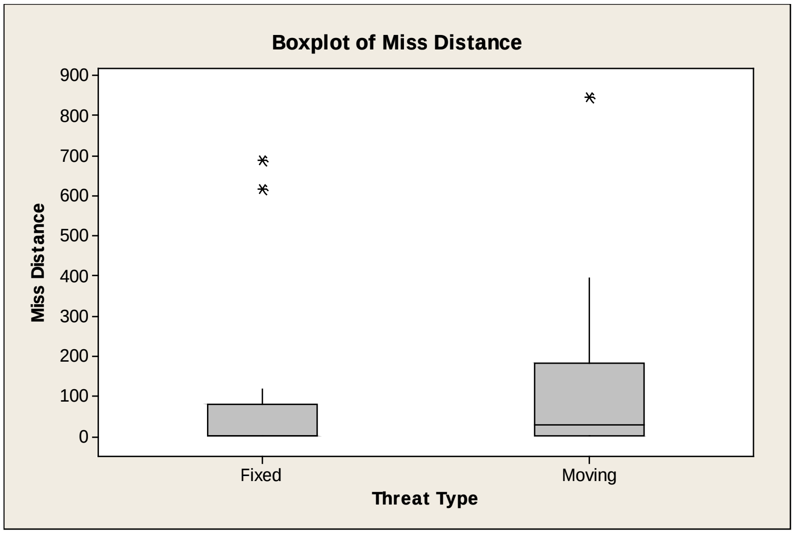
Kruskal-Wallis Test on Miss Distance

UAS Altitude (ft)	N	Median	Ave Rank	Z
500	16	32.840	15.8	-0.41
2,000	16	3.090	17.2	0.41
Overall	32		16.5	

H = 0.17   DF = 1   P = 0.678

Figure 63 - Kruskal-Wallis Test: Miss Distance versus UAS Altitude (ft)

The results of the Kruskal-Wallis Test for miss distance vs. target type are shown in Figure 64. In this case the null hypothesis failed to be rejected, therefore the null hypothesis was accepted, which implies target type is not a statistically significant factor on the results observed for miss distance.



Kruskal-Wallis Test on Miss Distance

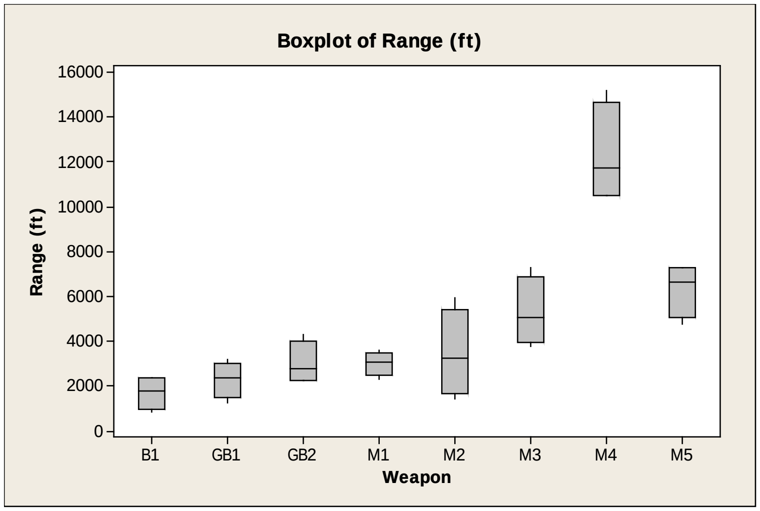
Target Type	N	Median	Ave Rank	Z
Fixed	16	1.335	15.1	-0.87
Moving	16	28.270	17.9	0.87
Overall	32		16.5	

H = 0.24   DF = 1   P = 0.624

H = 0.24   DF = 1   P = 0.624   (adjusted for ties)

Figure 64 - Kruskal-Wallis Test: Miss Distance versus Target Type

The results of the Kruskal-Wallis Test for range vs. weapons are shown in Figure 65. From the results, weapon M-2 differed least from the mean rank for all observations and weapon M-4 had the highest rank and Bomb the lowest. In this case the null hypothesis, H_0, was rejected and the alternative hypothesis, H_1, was accepted, which implies the choice of weapon is a statistically significant factor on the results observed for range to target.



Kruskal-Wallis Test on Range (ft)

Weapon	N	Median	Ave Rank	Z
Bomb	4	1,762	5.1	-2.59
GB1	4	2,339	8.6	-1.79
GB2	4	2,765	12.3	-0.97
M1	4	3,038	13.3	-0.74
M2	4	3,220	14.8	-0.40
M3	4	5,043	22.4	1.34
M4	4	11,727	30.5	3.19
M5	4	6,623	25.1	1.97
Overall	32		16.5	

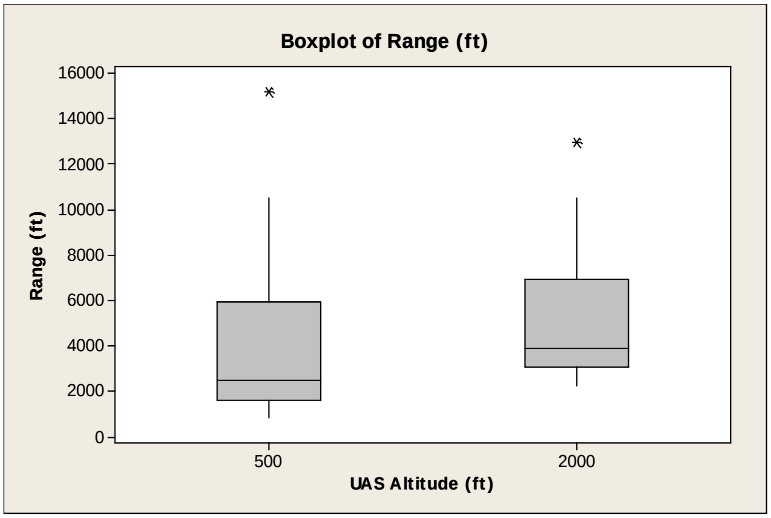
H = 24.00 DF = 7 P = 0.001

H = 24.05 DF = 7 P = 0.001 (adjusted for ties)

Figure 65 - Kruskal-Wallis Test: Range (ft) versus Weapon

The results of the Kruskal-Wallis Test for fire range vs. altitude are shown in Figure 66. In this case the null hypothesis failed to be rejected, therefore the null hypothesis was

accepted which implies altitude is not a statistically significant factor on the results observed for range to target.



Kruskal-Wallis Test on Range (ft)

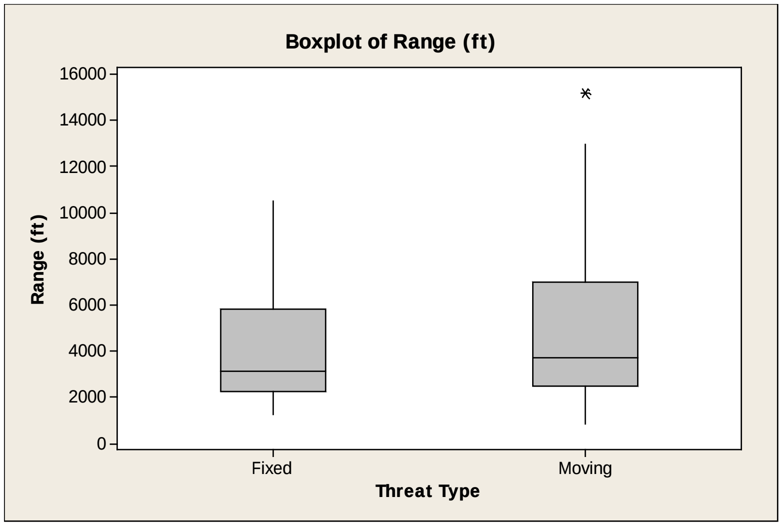
UAS Altitude (ft)	N	Median	Ave Rank	Z
500	16	2,461	14.3	-1.36
2,000	16	3,858	18.8	1.36
Overall	32		16.5	

H = 1.84 DF = 1 P = 0.175

H = 1.84 DF = 1 P = 0.174 (adjusted for ties)

Figure 66 - Kruskal-Wallis Test: Range (ft) versus UAS Altitude (ft)

The results of the Kruskal-Wallis Test for fire range vs. target type are shown in Figure 67. In this case the null hypothesis failed to be rejected, therefore the null hypothesis was accepted which implies target type is not a statistically significant factor on the results observed for range to target.



Kruskal-Wallis Test on Range (ft)

Target Type	N	Median	Ave Rank	Z
Fixed	16	3,129	15.1	-0.85
Moving	16	3,676	17.9	0.85
Overall	32		16.5	

H = 0.72   DF = 1   P = 0.396

H = 0.72   DF = 1   P = 0.396   (adjusted for ties)

Figure 67 - Kruskal-Wallis Test: Range (ft) versus Target Type

5. Modeling and Simulation Conclusions

The model results appear to indicate that the target type and altitude are not significantly significant factors that would influence the decision to pick one weapon over another. However, as expected, the weapon type is a statistically significant factor. From the data collected, the RUINS team believes, based on this analysis alone, that the GB-1 or M-4 weapons should be the primary weapons systems considered. It is recognized that this conclusion is dependent on the assumptions and algorithms in the M&S. However, the M&S results might reasonably be used to reduce the number of variables for an actual open-air test of candidate UAV/weapon combinations.

B. Modeling of Warhead Effects

1. Introduction

If the weapon being modeled is anything other than a simple projectile, some means of judging the effects on the target resulting from the explosion of a warhead must be included in any lethality analysis and weapon effectiveness tradeoffs. Warheads are described for the purposes of this study as some amount of explosive material encased in a housing designed for fragmentation upon detonation of the explosive. The explosion of the warhead results in two different types of damage to the target. A measure of warhead effectiveness is the probability of kill (P_K). This measure is the result of the combination of the assessment of the target vulnerabilities, damage functions, and effects of the warhead on the target. The P_K of a target is a statistical measure of the likelihood that a target will be removed from combat. The overall P_K, due to the detonation of a warhead, is a combination of the probability of kill due to the blast ($P_{K|BLAST}$) and the probability of kill due to the warhead fragmentation ($P_{K|FRAG}$). For the purposes of this report, only the effects of $P_{K|FRAG}$ will be included in estimations of P_K.

When an explosive material is detonated, a chemical reaction nearly instantaneously converts the explosive from either solid or liquid form to gas in a violent reaction. Large amounts of energy are released during the conversion. The results of the explosion are a region of highly compressed gas and various solid residues that are remains of the explosive and its housing. The compressed gas, called the blast, expands rapidly to occupy a volume many times greater than the original explosive volume.

Blast can damage a target by one of two methods: diffraction and drag loading. Diffraction loading is the application of pressure as the shock wave passes over an object. It is associated with diffraction as the shock wave bends around the target while passing it. Loading pressure is applied to several of a target's surfaces almost instantaneously. A building would be subjected to the pressure on the front and roof at the same time. To illustrate how destructive this could be, a 10 ft cubicle building exposed to 15 pounds per square inch (psi) over pressure would experience diffraction loading on the front, roof, and two sides simultaneously totaling 864,000 pounds of force (lb_F) (Federation of American Scientists 1998).

Drag loading is a result of dynamic pressure. Drag loading is the aerodynamic force that acts on a surface perpendicular to the shock wave front. Dynamic loading applied to a 10 foot cubicle building with a dynamic pressure of 5 psi would experience a drag load totaling 72,000 lb_F. Drag loading is typically applied for longer than diffraction loading and drag loads tend to reverse direction, resulting in forces that can destroy buildings (Federation of American Scientists 1998). Figure 68 shows diffraction and drag loading.

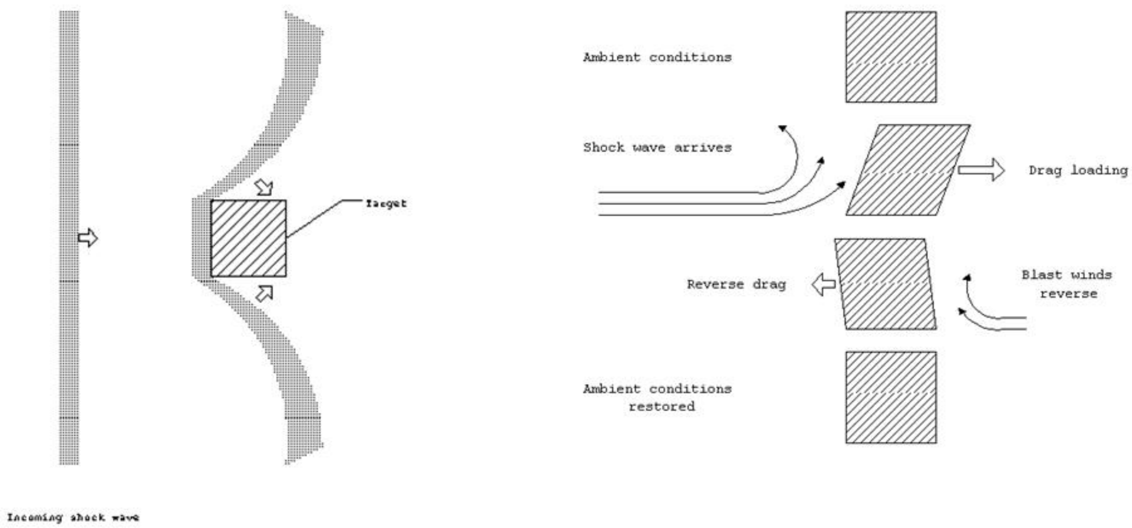


Figure 68 - Loading Pressures from (Federation of American Scientists 1998)

The expanding gas will also cause the warhead housing to fragment and disperse at high speeds, overtaking the blast shock. The velocity of the fragments does not decrease as rapidly as that of the shock, extending the effect of the warhead. The fragments impact the targets and cause penetration damage, maximizing the warhead effect against the enemy (Driels 2004).

The damage to a target from fragmentation can be found from the kinetic energy. For personnel, the minimum amount of kinetic energy to lethal is 100 Joules (J). This is roughly equivalent to a .22 caliber long bullet (40 grains) traveling at 1000 feet per second (fps). An increased level of damage is 1000 J, which correlates to a .357 caliber jacketed soft point bullet (158 grains) traveling at 1400 fps. This can be lethal to personnel

depending on where they are hit. 4000J is sufficient to penetrate body armor and correlates to a 7.62 caliber full metal jacket or a .30-06 caliber armor piercing bullet (166 grains) at a velocity of 2750 fps (Federation of American Scientists 1998). Table 35 shows the kinetic energy required for a number of targets and the corresponding P_K.

Table 35 - Damage and Corresponding P_K (Federation of American Scientists 1998)

	Fragment Energy in kJ		
Target	Light Damage ($P_K = 0.1$)	Moderate Damage ($P_K = 0.5$)	Heavy Damage ($P_K = 0.9$)
Personnel	0.1	1	4
Aircraft	4	10	20
Armored Vehicle	10	500	1,000

Fragments do not lose their energy as quickly as the blast. A fragment from a hand grenade can be lethal up to 100 m, while the effects of the blast may be minimal at that range. However, the probability of being hit by a fragment at 100 m is very low. There are a finite number of fragments distributed in all directions. Assuming spherical fragment dispersion, the average number striking a target will be directly related to $1/R^2$, where R is the range from the exploding warhead. The number of fragment hits can be found using Equation 21; however, the equation is not valid for $R < \sqrt{(1/4\pi)}$, when the calculated number of fragment hits begins to exceed the total fragments of the warhead.

Equation 21 - Number of Fragment Hits from (Federation of American Scientists 1998)

Where

N_{HITS} is the expected number of fragments hitting the target;

N_o is the initial number of fragments from the warhead;

A is the frontal area of the target presented to the warhead;

R is the range of the target to the warhead.

Complete assessment of the warhead effects requires detailed knowledge of the engagement geometries, target vulnerabilities, and weapon characteristics. The fragment trajectories resulting from one angle of attack may not be the same as those from a slightly different angle.

Warhead fragmentation was modeled during development, but the only way to determine lethality was to perform an arena test. The left drawing in Figure 69 is an example of fragmentation contours for a weapon not detonating normal to the target. The contour lines dividing different thresholds of P_K are difficult to predict and not symmetrical about the center of detonation. A different impact angle might yield a different set of profiles. This yields a variety of damage functions from single engagement geometry, as shown in the right drawing, making accurate predictions of weapon performance for different conditions difficult. In contrast, a blast-only damage function would remain more symmetrical about the detonation point (Schaffer 1966).

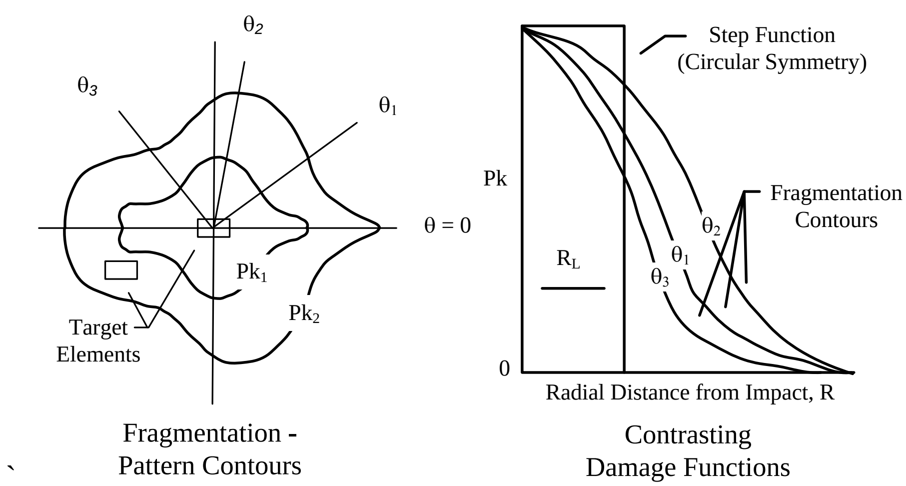


Figure 69 - Example Damage Functions (Schaffer 1966)

The P_K will be the product of the probability that a target will be hit by a fragment and the probability of incapacitation if hit as shown in Equation 22. Multiple fragment hits will be handled with Equation 23. The miss distance was determined from published data for warhead weights.

Equation 22 - Overall P_K for a Target (Schaffer 1966)

Where

= probability of being hit;

= probability of incapacitation if hit

Equation 23 - P_K for Multiple Hits (Schaffer 1966)

Where

= P_K if hit;

N_{HITS} = the number of fragment hits

To determine the target vulnerable area, several assumptions were made. For the human target, ergonomic data was used for a European in the 95 percentile. The measurements were taken for the chest, neck and head and an area was calculated. Figure 70 shows the ergonomic data. For the human, the vulnerable area was found to be $0.264m^2$. For the truck target, a 1990 Toyota truck was used. The analysis was for a mobility kill of the truck; this was assumed to be a flat tire or overheated truck. The stock tire was determined to be a P225/50R/15S. This relates to a tire diameter of 0.381 m with a side wall length of 0.112 m. A replacement radiator was found with dimensions of 0.457 by 0.717 meters. These accumulated to a vulnerable area of $0.559m^2$.

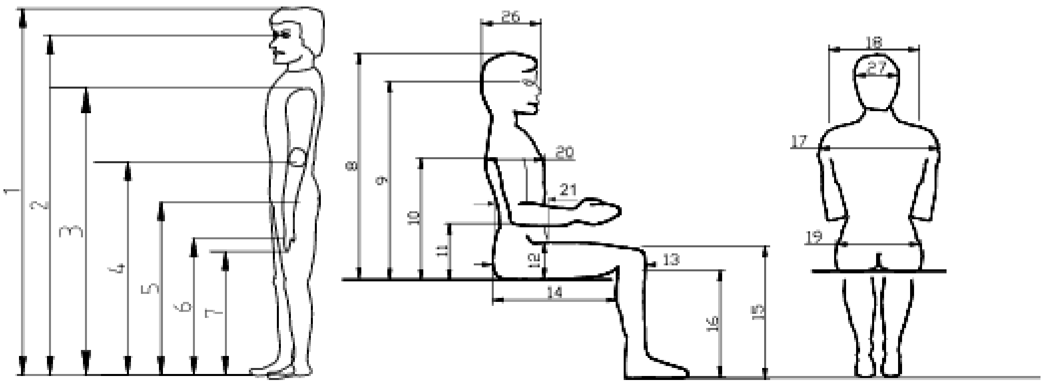


Figure 70 - Ergonomics Data from (Royal Mechanical 2010)

2. Candidate Weapon Warheads Characteristics and Results

The weapons that remained after down select were evaluated to determine warhead weight. Assuming a charge-to-metal ratio of one, the total mass of fragments was determined. Individual fragment size was calculated based on a 2000 m/s fragment speed and the kinetic energy necessary to produce a 0.7 $P_{K|HIT}$ for a single fragment hit of a human. A single exception to this was the GB-2 warhead. This warhead produces a single explosively formed projectile and twelve fragments, resulting in much higher kinetic energy per fragment. The resulting number of fragments for the candidate weapons is shown in Table 36.

Table 36 - Warhead Parameters

Weapon	Warhead weight (kg)	Total Fragment Weight (kg)	Number of fragments	Kinetic Energy (Joules)
Bomb	4.54	2.27	1,452.56	2,611.31
GB-1	1.81	0.91	581.03	2,611.31
GB-2	2.27	1.13	13.00	145,887.97
M-1	8.39	4.20	2,687.24	2,611.31
M-2	7.98	3.99	2,556.51	2,611.31
M-3	3.00	1.50	960.14	2,611.31
M-4	0.91	0.45	290.51	2,611.31
M-5	0.29	0.14	90.79	2,611.31

Once the total number of fragments was known for the warheads, Equation 21 was used to determine the number of fragment hits as a function of radial distance. Equation

23 was then used to determine the P_K for multiple fragment hits, and Equation 22 was used for single fragment hits. The resulting P_K was calculated to 30 m for a human target and is shown in Figure 71. Figure 72 shows the resulting P_K for the truck target. The analysis assumes that all of the fragments are the same size and that all of the fragments are uniformly dispersed.

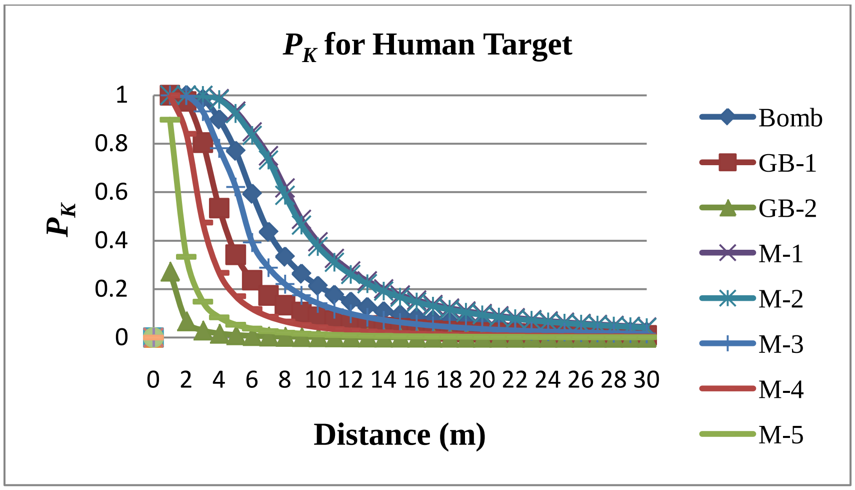


Figure 71 - P_K of a Human as a Function of Distance from Detonation

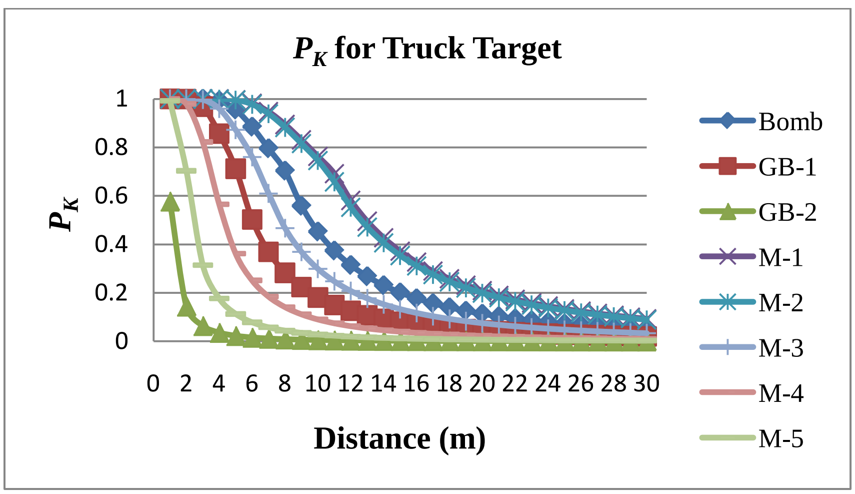


Figure 72 - P_K of a Truck as a Function of Distance from Detonation

The weapons miss distance data was taken for the Tier II UAS at its maximum and minimum altitude and a P_K was determined for the human and truck target. For the fixed

target scenario, two primary targets were assumed to be within 0.5 m of the targeted point. A secondary target was positioned 2.67 m from the targeted point. The results of the analysis can be seen in Table 37 and Table 38. As mentioned previously, the equation for number of hits is not valid at small miss distances and can indicate more hits than the total number of fragments. In these cases, the total number of fragments possible was used.

Table 37 - P_K for Human Target

Scenario Name	Aim Point Miss Distance (m)	Fragment Hits (primary targets)	P_K (human)	Fragment Hits (secondary target)	P_K Look Out (human)
T2-FT-B-MAX	687.47	0.00	0.000	0.00	0.000
T2-FT-GB1-MAX	0.24	211.92	1.000	1.44	0.823
T2-FT-GB2-MAX	0.30	3.03	0.974	0.03	0.021
T2-FT-M1-MAX	0.44	291.61	1.000	5.84	0.999
T2-FT-M2-MAX	0.42	304.47	1.000	5.63	0.999
T2-FT-M3-MAX	0.00	960.14	1.000	2.83	0.967
T2-FT-M4-MAX	16.73	0.02	0.015	0.02	0.011
T2-FT-M5-MAX	1,999.02	0.00	0.000	0.00	0.000
T2-FT-B-MIN	802.50	0.00	0.000	0.00	0.000
T2-FT-GB1-MIN	0.37	89.16	1.000	1.32	0.796
T2-FT-GB2-MIN	0.38	1.89	0.897	0.03	0.021
T2-FT-M1-MIN	454.89	0.00	0.000	0.00	0.000
T2-FT-M2-MIN	0.41	319.50	1.000	5.66	0.999
T2-FT-M3-MIN	335.09	0.00	0.000	0.00	0.000
T2-FT-M4-MIN	23.37	0.01	0.008	0.01	0.006
T2-FT-M5-MIN	802.5	0.00	0.000	0.00	0.000

Table 38 - P_K for Truck Target

Scenario Name	Target Miss Distance (m)	Fragment Hits	P_K(truck)
T2-MT-B-MAX	846.74	0.00	0.000
T2-MT-GB1-MAX	0.44	133.50	1.000
T2-MT-GB2-2-MAX	0.71	1.15	0.548
T2-MT-M1-MAX	0.39	785.92	1.000
T2-MT-M2-MAX	1.15	85.99	1.000
T2-MT-M3-MAX	0.00	960.14	1.000
T2-MT-M4-MAX	18.11	0.04	0.020
T2-MT-M5-MAX	2,017.77	0.00	0.000
T2-MT-B-MIN	302.58	0.00	0.000
T2-MT-GB1-MIN	0.43	139.79	1.000
T2-MT-GB2-MIN	0.4	3.61	0.918
T2-MT-M1-MIN	67.74	0.03	0.013
T2-MT-M2-MIN	0.43	615.05	1.000
T2-MT-M3-MIN	0.83	62.00	1.000
T2-MT-M4-MIN	39.73	0.01	0.004
T2-MT-M5-MIN	857.02	0.00	0.000

3. Warhead Lethality Radius

A typical performance measure used in the evaluation of various warhead options is the lethal radius. This term has been defined as the radius from the warhead at which the probability of the target being damaged enough to remove it from action (P_K) is 0.5. Only fragmentation effects were considered in this analysis. For use in the analysis, Equation 21, Equation 22, and Equation 23 were reorganized to directly provide this measure for each of the candidate weapons. This reorganization results in Equation 24.

Equation 24 - Lethality Radius Calculation

For purposes of this investigation, different values of $P_{K|HIT}$ were used for the human and vehicle target due to differences in the target scenarios, as well as different area values. For this reason, two values of lethality radius were calculated for each candidate weapon. P_K of 0.5 was used in both cases.

Table 39 - Lethality Radius for Candidate Weapons

Weapon	Fragments per Weapon	Radius for Human Target (meters) ($P_{K\|HIT}$ = 0.7, A = 0.264m^2)	Radius for Vehicle Target (meters) ($P_{K\|HIT}$ = 0.5, A = 0.559m^2)
Bomb	1,452.6	7.28	8.04
GB-1	581.0	4.60	5.08
GB-2	13.0	0.69	0.76
M1	2,687.2	9.90	10.93
M2	2,556.5	9.66	10.66
M3	960.1	5.92	6.54
M4	290.5	3.26	3.59
M5	90.8	1.82	2.01

4. Warhead Collateral Damage

For complete knowledge of the effects the candidate weapon may have if used in battle, some notion of the potential collateral damage effects are needed. To assess these effects, the population density of an example city was used. Baghdad is one of the world's more densely populated cites, with a population estimated at 5.5 million people located in an area of 596 square kilometers (City Mayors 2007).

An area of 100m^2 was used for performing the analysis. Within this area, targets in the quantities determined by the above described population density were positioned according to a random uniform distribution. The vulnerable area of each target was assumed to be that representing a human. The damage functions described earlier were used to determine differing levels of damage on the population within the area. As the damage function used has a spherical distribution, a radius of 50m was used to limit the range of the analysis. A warhead was considered detonated at the (0, 0) location. Approximate numbers of those suffering various levels of damage were then assessed

based on their distance from the point of detonation. Each detonation was considered an independent event. Ten thousand detonations were simulated using each warhead type, with a random positioning of targets occurring prior to each detonation. Figure 73 illustrates the random distribution of targets and the increase in area coverage as the quantities of independent detonations were increased. The marker size of each data point used in the far right illustration has been reduced to allow better visualization of the target area coverage. The circles in Figure 73 illustrate the study area boundary. Targets outside of these circles were not considered in the analysis.

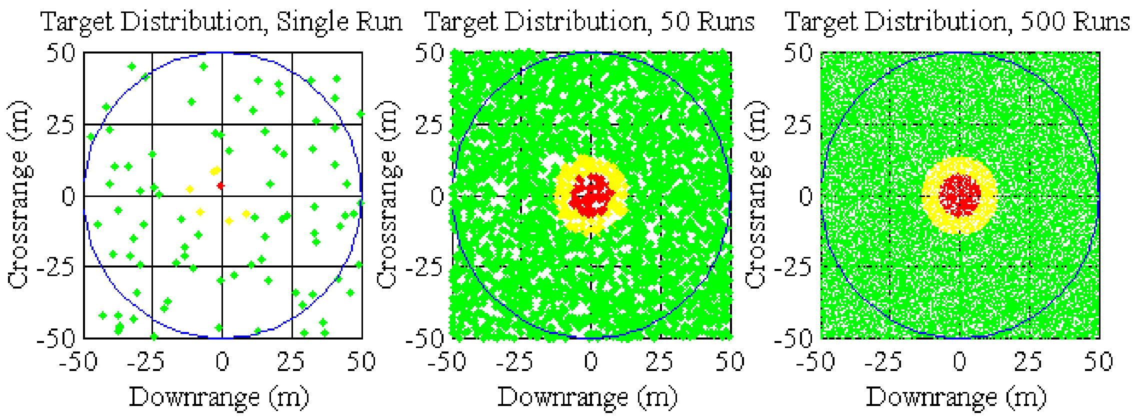


Figure 73 - Collateral Damage Random Target Positioning

For each target, three possible levels of damage were considered. From the preceding discussions, $P_K \geq 0.7$ indicates a hit in the target vulnerable area by at least one warhead fragment. This level of damage was considered severe, and is indicated by the red markers in Figure 73. A moderate level of damage was defined to be $0.3 \leq P_K < 0.7$ and is indicated by yellow markers. A light level of damage was defined as $P_K < 0.3$ and is indicated by green markers.

Total quantities of targets suffering each of the three damage categories were determined after 10,000 independent detonations of each warhead candidate. The data was then analyzed to determine percentage of the sample at each level of damage. Percentages were used as they are applicable with differing population densities. Using

the percentages presented in Table 40 and an approximate population density, estimated collateral damages may be calculated using Equation 25.

Table 40 - Estimated Collateral Damage Percentages by Candidate Weapon

Weapon	$P_K >= 0.7$	$0.3 <= P_K < 0.7$	$P_K < 0.3$
Bomb	1.24%	2.89%	95.87%
GB-1	0.49%	1.17%	98.34%
GB-2	0.01%	0.03%	99.97%
M-1	2.24%	5.37%	92.78%
M-2	2.14%	5.08%	92.78%
M-3	0.80%	1.91%	97.29%
M-4	0.24%	0.57%	99.20%
M-5	0.08%	0.18%	99.74%

Equation 25 - Collateral Damage Estimation Equation

Where

= Estimated Collateral Damage (persons),

= Population Density (persons/meter^2),

= Area of a circle with radius of 50 meters (meters^2), and

= Estimated Collateral Damage Percentage from Table 40 (dimensionless)

For additional insight into the possible effects of collateral damage, the expected radius associated with each P_K level was calculated using a variation of Equation 24. These may allow rapid assessment of collateral damage potential and target damage potential due to weapon miss distances. These calculated distances are presented in Table 41.

Table 41 - Target Distance from Point of Detonation for P_K Levels

Weapon	Radius where P_K = 0.7 (meters)	Radius where P_K = 0.3 (meters)
Bomb	5.5	10.1
GB-1	3.5	6.4
GB-2	0.5	1.0
M-1	7.5	13.8
M-2	7.3	13.5
M-3	4.5	8.3
M-4	2.5	4.5
M-5	1.4	2.5

C. Aerodynamic Performance Analysis

Part of the weaponization feasibility study was to ensure that the addition of a weapon would not significantly impact the aerodynamic performance of the UAV. For the purposes of this study a significant impact was considered to be greater than 5 percent reduction in the existing capability of the UAV. A full set of aerodynamic properties for the Shadow 600 were available with the NGTS modeling tools that were used for the weapon effectiveness modeling and simulation efforts. While the parameters associated with the Shadow 600 were not the same as those that would be associated with the surrogate UAV, the relative impact of adding a weapon was assumed to be similar.

1. Methods and Initial Data

Basic aerodynamic lift and drag calculations were performed to determine the impact on velocity, endurance, and distance traveled. The basic equations for lift and drag come from the forces that act upon the UAV. Figure 74 is a free body diagram depicting the forces acting on a UAV. In this case, it was assumed that there were no winds and that the thrust always acted along the body axis of the UAV.

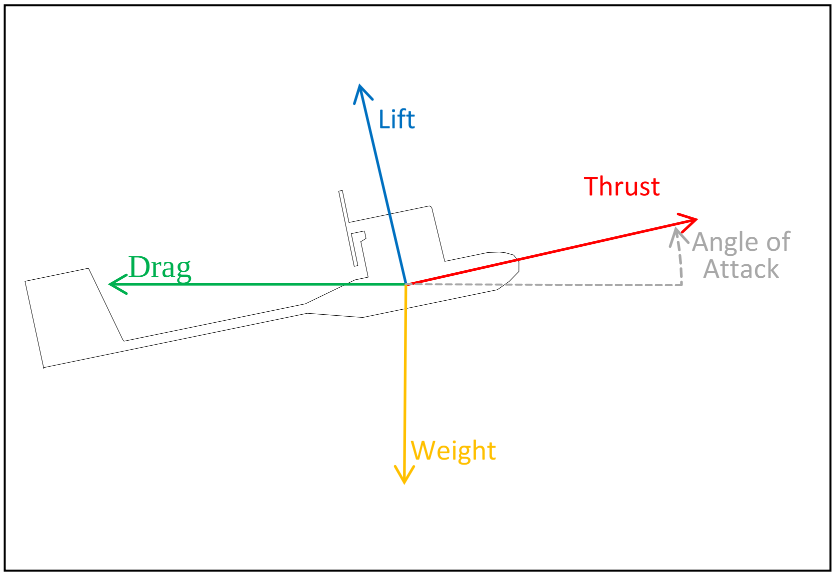


Figure 74 - UAV Aerodynamic Forces

The Shadow 600 data used in the analysis was obtained from the NGTS model data and Jane's Unmanned Aerial Vehicles and Targets. Data used in this analysis included maximum, cruise, and loiter velocities, coefficient of drag as a function of coefficient of lift, angle of attack as a function of coefficient of lift, wing area, empty weight, fuel capacity, and fuel flow rates. Table 42, Figure 75, and Figure 76 summarize the data that was used to determine the baseline Shadow 600 aerodynamic performance.

Table 42 - Shadow 600 Parameters for Analysis (IHS Global Limited 2010)

Shadow 600 Property	Value	Units
Empty Weight	327.00	lbf
Fuel Capacity	22.50	gal
Fuel Weight	4.86	lbs/gal
Sensor Weight	35.00	lbf
Baseline Weight	471.35	lbf
Wing Area, S	40.41	ft^2
Max Velocity	104.00	kts
Cruise Velocity	75.00	kts
Loiter Velocity	65.00	kts
Max Fuel Flow	27.65	gal/hr
Cruise Fuel Flow	20.74	gal/hr
Loiter Fuel Flow	17.97	Gal/hr

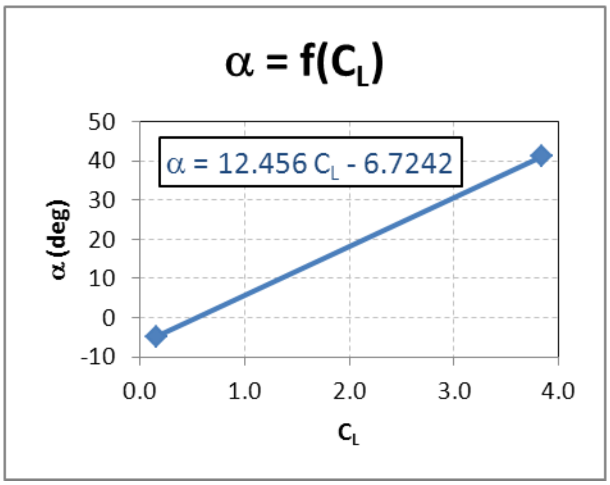


Figure 75 - Shadow 600 Angle of Attack as a Function of Lift

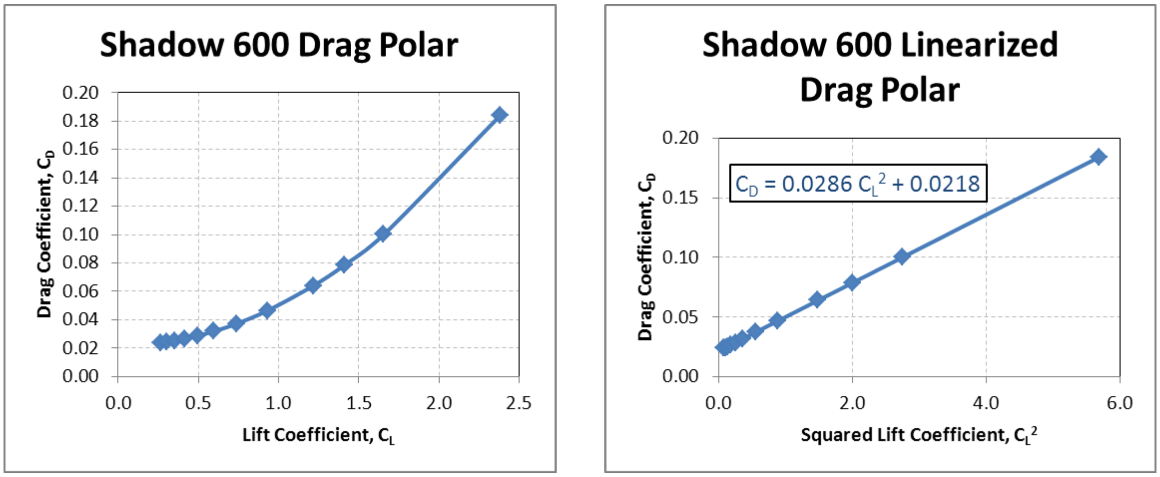


Figure 76 - Shadow 600 Drag Polar Data

2. Calculations

With the Shadow 600 aerodynamic data, it was possible to find the coefficient of lift that resulted in level flight for known velocities through the following equations. Standard atmosphere was assumed to determine the air density as a function of altitude.

Equation 26 - Required Lift for Level Flight from (Anderson 2011)

Equation 27 - Required Thrust for Constant Velocity from (Anderson 2011)

Equation 28 - Total Drag as a Function of Induced Drag from (Anderson 2011)

Equation 29 - Angle of Attack as a Function Lift from (Anderson 2011)

–

Equation 30 - Lift for Level Flight with Known Velocity with Substitutions

Where:

Once the baseline performance was established, it was possible to determine the degraded performance by assuming values for additional weight and drag from the weapon, the weapon hardware, and the weapon management system. The analysis considered total weapon system weights from 15 to 60 pounds. It also assumed that the drag coefficient could increase anywhere from 0 percent to 10 percent. In order to determine the impact on lift and drag from the addition of a weapon, it was necessary to use a different set of equations. In the baseline analysis, the velocity was known, but if the same throttle settings are used, the resulting velocity will be reduced with additional weapon weight and drag.

Equation 31 - Lift for Level Flight with Known Thrust from (Anderson 2011)

Equation 32 - New Required Thrust for Constant Velocity from (Anderson 2011)

Equation 33 - Required Lift for Level Flight with Known Thrust with Substitutions

3. Results

MATLAB was used to evaluate the lift and drag equations over a range of altitudes, velocities, weapon weights, assumed drag increases, and time. The results indicated that the addition of weapons could have a significant impact on the performance of the Shadow 600. This is clearly shown in the following series of figures in which maximum velocity is depicted as a function of the percent increase in drag and the additional weapon weight. The shading represents the percent difference from the baseline case of 0 percent increase in drag and 0 pounds added. Green represents a 0–to 4 percent reduction, yellow represents a 4–5 percent reduction, and red represents any reduction greater than 5 percent. The values along the x-axis simulate the effect of increasing the drag only and offsetting the weight of the weapon by having less fuel aboard the UAV. The values along the y-axis simulate the effect of carrying the weapon internally and only increasing the weight. These options are not actually being considered, and were not investigated any further, but they are interesting byproducts of the analysis. The remaining region of the charts is the primary area of interest, and as they clearly show, the performance falls off rather quickly.

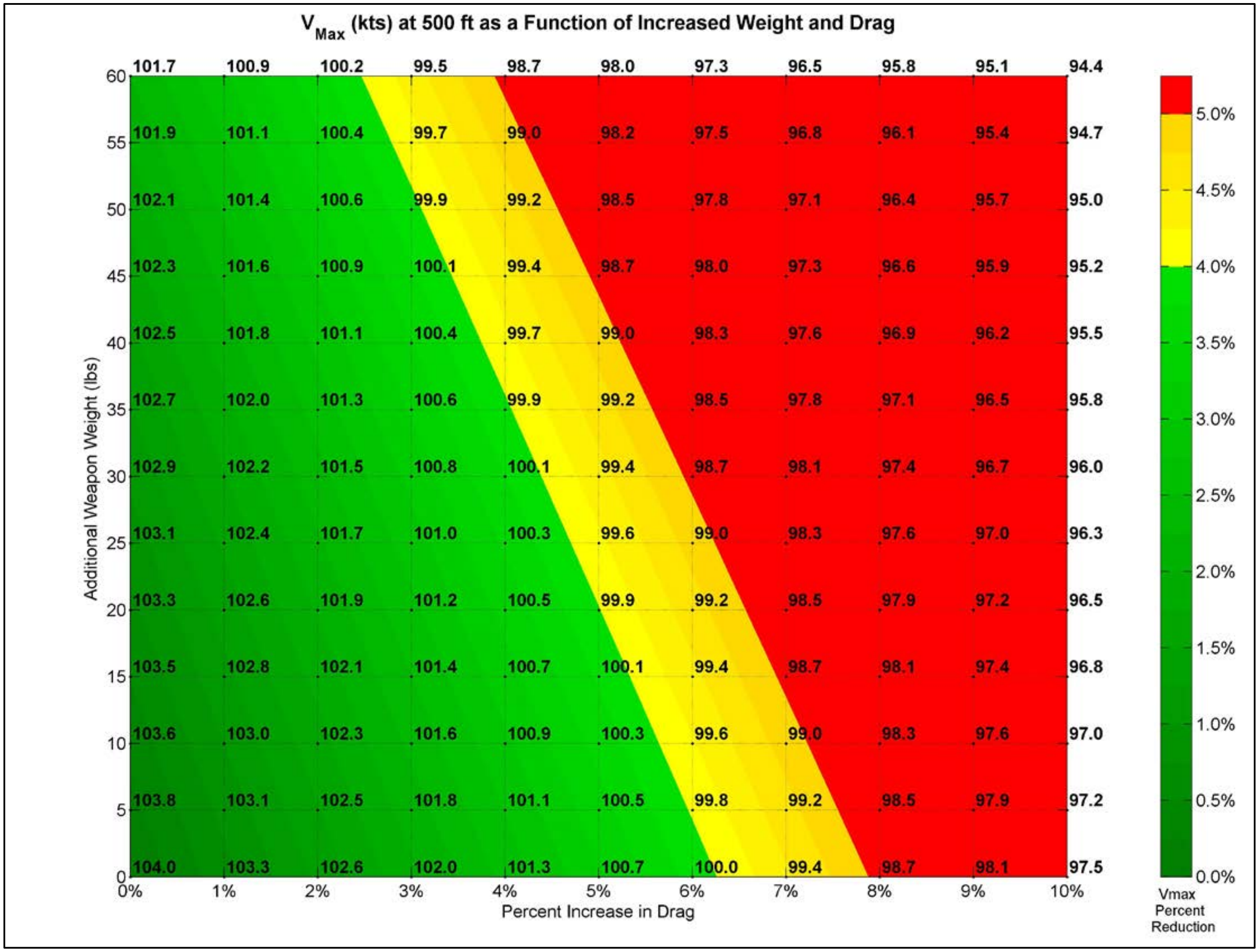


Figure 77 - Reduction in Maximum Velocity at 500 feet

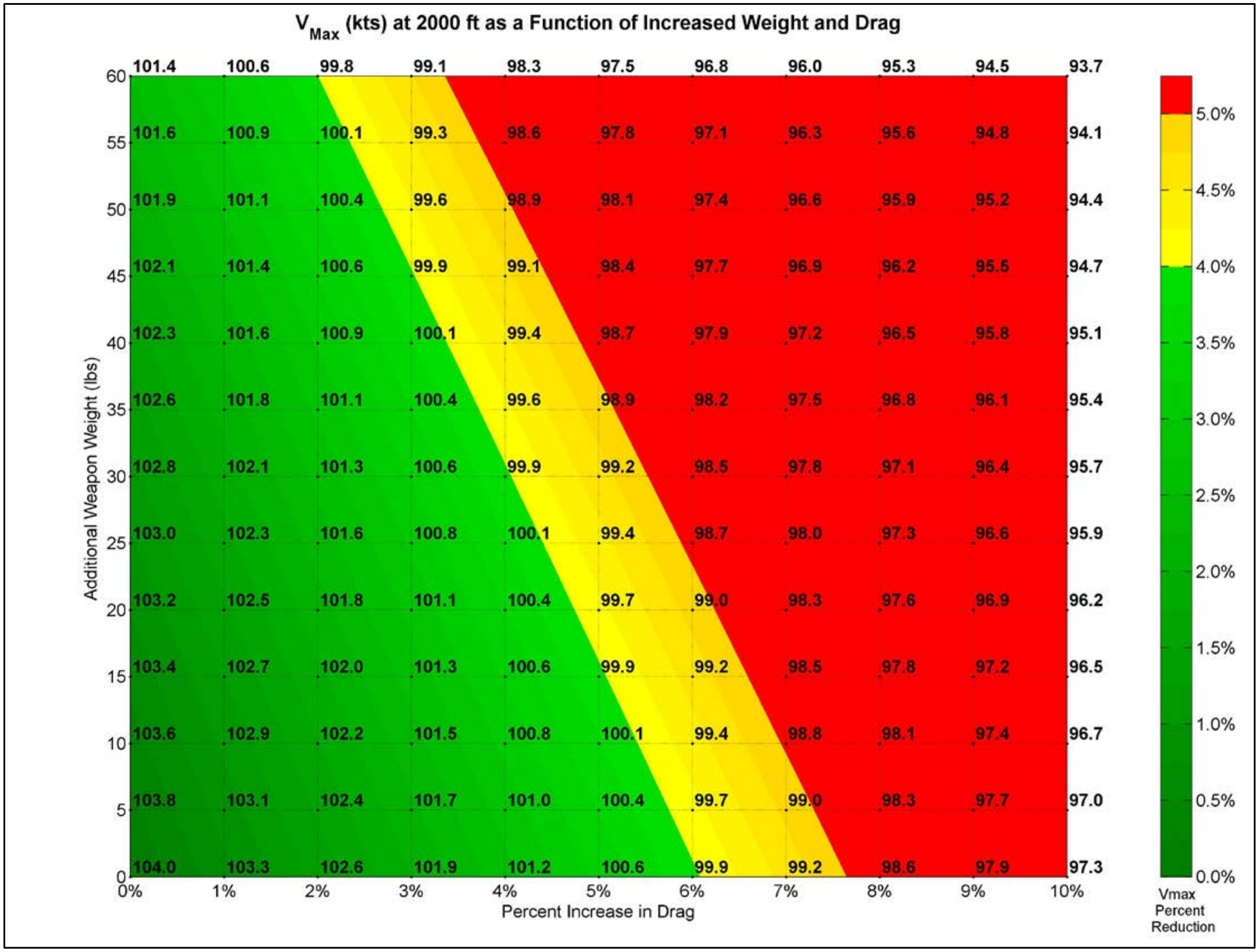


Figure 78 - Reduction in Maximum Velocity at 2,000 feet

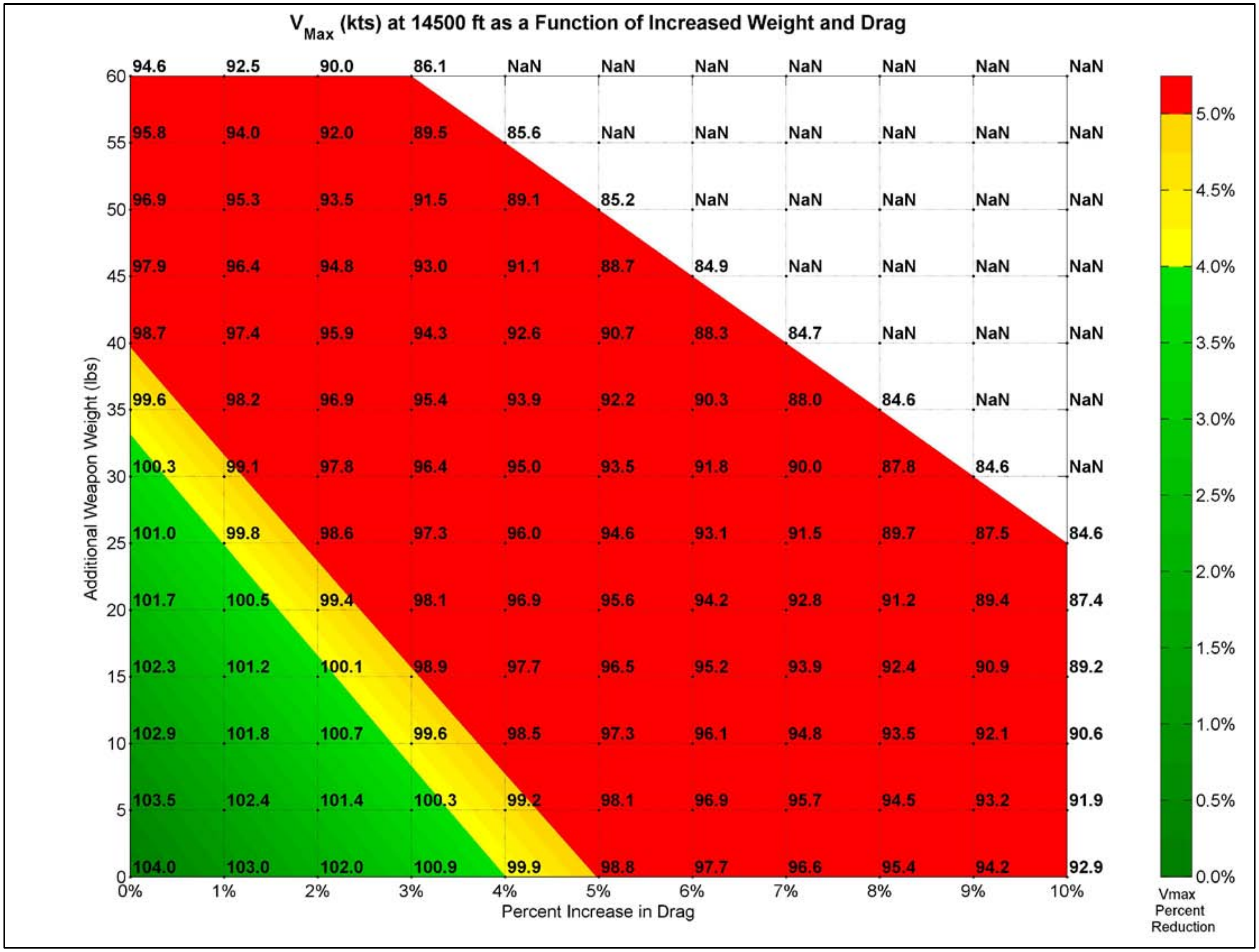


Figure 79 - Reduction in Maximum Velocity at 14,500 feet

In the 500 and 2,000 feet cases, level flight is still possible throughout the analyzed region, but the maximum velocity cannot be maintained within the 5 percent margin as the drag increases. However, the impact worsens with altitude, and level flight is not possible at the Tier II maximum defined altitude of 14,500 feet as weight and drag increase. This is indicated by the “NaN” values shown on the 14,500 feet plot. “NaN” was used as the output when MATLAB was unable to find a solution to the required lift equation. All the plots show that the effect of drag is much more significant than the effect of the additional weight. Any weapon system that would be considered should emphasize being “low-drag.”

The next area that was analyzed was the velocity over time. This was important to know because the additional weight and drag of a weapon made it nearly impossible to fly at anything but 100 percent throttle and maximum velocity with a full load of fuel. By looking at velocity over time, it was possible to see at what point level flight became possible as fuel burned off. Loiter velocity was of the most interest because the scenarios that were defined assumed that the UAV would be in a search pattern at loiter velocity. The following figure shows the maximum and loiter velocities for 15, 30, 45, and 60 pound weapon systems at 2,000 feet. Based on the team’s assumption that the weapon management system (WMS) weighs 10 pounds and the mounting hardware is equal in weight to the actual weapon, the 15 pound weapon system is an approximate representation of the Switchblade. On the other end, the 60 pound weapon system is an approximate representation of the Stinger or SPIKE-MR/LR. The dots indicate the point at which enough fuel has been burned to transition from maximum to loiter velocity. At 100 percent throttle, the Shadow 600 model data assumed a 27.65 pound per hour fuel consumption rate, which allowed for almost 4 hours of endurance. At loiter throttle, a 17.97 pound per hour consumption rate was assumed, which allowed for slightly more than 6 hours of endurance. This conflicts with the 12–14 hours of endurance claimed by Jane’s (IHS Global Limited 2010) for the Shadow 600 endurance, but 6 hours is representative of the other members of the Shadow family. The top row of graphs shows the flight time at maximum velocity, and the bottom row shows the remaining flight time once a transition to loiter has been made.

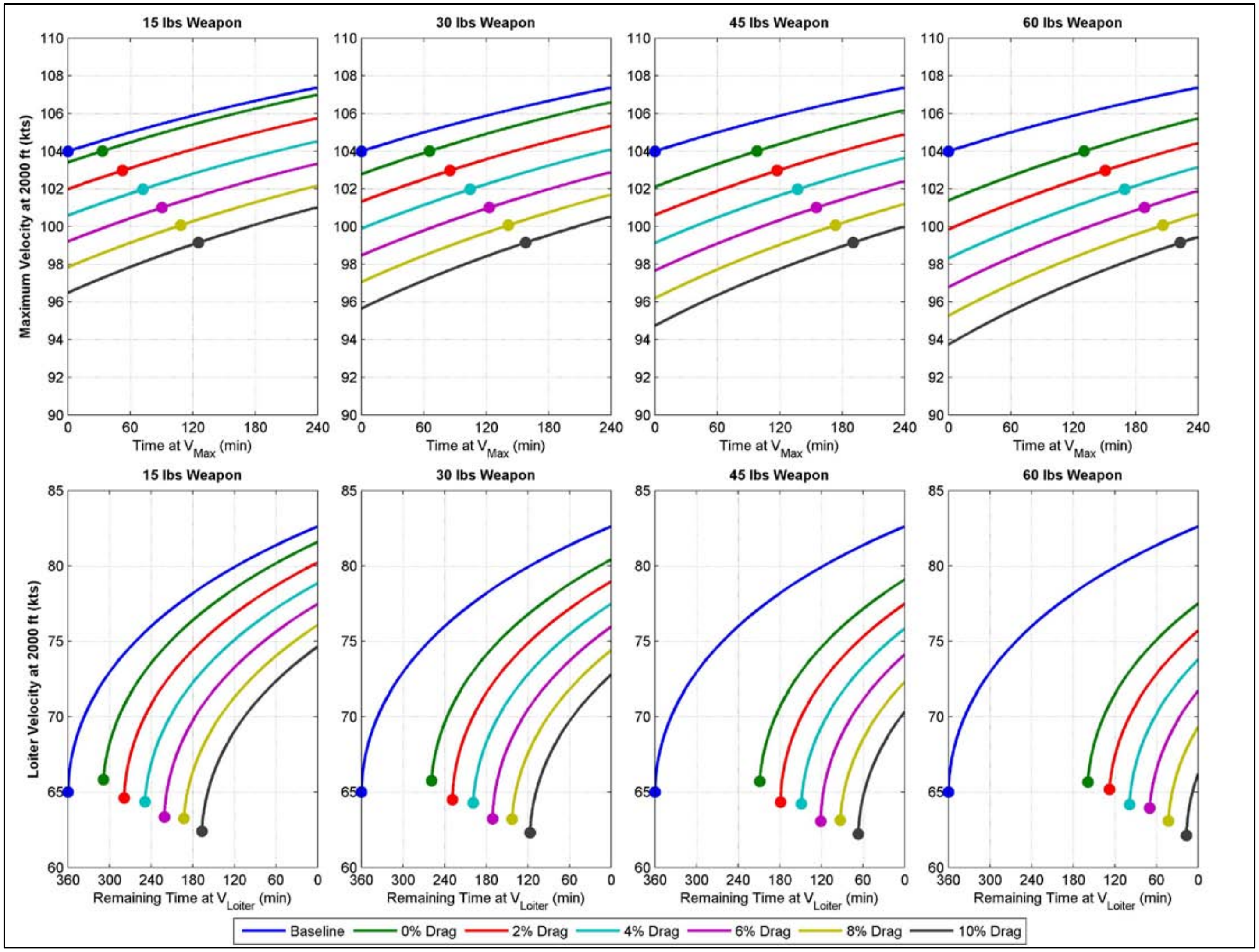


Figure 80 - Shadow 600 Maximum and Loiter Velocity over Time

Due to a lack of real Shadow 600 data, it was assumed that the maximum and loiter velocities were achieved with a full load of fuel. Furthermore, it was assumed that the maximum and loiter velocities corresponded to a constant throttle percentage and thrust. Therefore, as the weight of fuel is reduced over time, the angle of attack declines to maintain level flight and the velocity increases. These graphs again show that drag is a more significant factor than weight.

4. MOE / MOP Impact Assessment

Following the initial analysis, the results were applied to the screened Tier II candidate weapons from Table 28 to assess the MOE 1.1.2 Minimize Endurance & Performance Impacts on Aerial Vehicle. The three MOPs that supported this MOE were MOP 1.2.2.1 Impact to Mission Time on Station, MOP 1.2.2.2 Impact to Maximum UAV Range, and MOP 1.2.2.3 Impact to Maximum Speed. The additional weight and drag of these weapon systems had a negative impact on all three MOPs. The impacts of the addition of single and where applicable multiple weapons were considered at the selected altitude of 2000 feet. Interpolation was used to calculate performance for each of the candidate weapon systems. Red was used to indicate a significant impact of greater than 5 percent reduction in performance. Yellow was used to show impacts between 4 percent and 5 percent reduction in performance. Green was used to show impacts less than 4 percent.

In order to determine the performance impacts for a specific candidate weapon system, it was required to determine the exact amount of additional weight that would be added to the UAV from the weapon, the mounting and launcher hardware, and the WMS. Table 43 shows the total weights for single and maximum configurations of the Tier II candidate weapons.

Table 43 - Total Weight for Screened Tier II Candidate Weapons

Weapon	WMS Weight (lbs)	Weapon Weight (lbs)	Mounting Weight (Each) (lbs)	Maximum Rounds	Total Single Weapon Weight (lbs)	Maximum Rounds Weapon Weight (lbs)
Bomb	10	10	10	2	30	50
GB-1		6	10	3	26	58
GB-2		10	10	2	30	50
M-1		26	26	1	62	62
M-2		23.1	23.1	1	56.2	56.2
M-3		23	23	1	56	56
M-4		5.3	5.3	4	20.6	52.4
M-5		2.2	2.2	10	14.4	54

The second consideration is the amount of additional drag that will be created. Wind tunnel data would be required to determine the actual drag impact of a particular weapon and mounting hardware installation on the Shadow 600, but this was not possible. To come up with a reasonable estimate for the drag coefficient increase, it was assumed that the ratio of the baseline Shadow 600 cross-sectional area to the “with weapon” cross-sectional area would be equal to the baseline and “with weapon” drag coefficient ratio. Therefore, a 5 percent increase in the cross-sectional area would result in a 5 percent increase in drag. Available data was used to determine the cross-sectional area along the main body axis for each candidate weapon, but assumptions were required to account for launcher and mounting hardware, weapon fins and other protrusions, and potential off-axis mounting angles. For all weapons, a factor of 2 was used to account for the additional area beyond the on-axis weapon cross-section. Furthermore, it was assumed that there was no masking when multiple weapons were loaded and that the full cross-sectional area of each weapon was added to the total to create a worst-case scenario. Table 44 shows the cross-sectional areas that were assumed for each candidate weapon system.

Table 44 - Total Cross-Sectional Area for Screened Tier II Candidate Weapons

Weapon	Maximum Rounds	Dimensions (D / HxW) (in)		Weapon Cross-Section (in^2)	Additional Cross-Section (in^2)	Total Single Weapon Cross-Section (in^2)	Maximum Round Cross-Section (in^2)
Bomb	2	5		19.6	39.3	58.9	117.8
GB-1	3	2.75		5.9	11.9	17.8	53.5
GB-2	2	5		19.6	39.3	58.9	117.8
M-1	1	5		19.6	39.3	58.9	58.9
M-2	1	4.2		13.9	27.7	41.6	41.6
M-3	1	2.75		5.9	11.9	17.8	17.8
M-4	4	2.25		4.0	8.0	11.9	47.7
M-5	10	2.25	2.25	10.1	10.1	15.2	151.9

Cross-sectional area data was not readily available for the Shadow 600, so it had to be estimated. A scaled drawing of the UAV, showing three orthographic views, was used in combination with the known dimensions of wing span, total length, and total height to obtain approximate dimensions for simple shapes that are present in the nose-on view.

Figure 81 shows these views, with the known dimensions in blue, and the scaled measurements in red. Table 45 provides details on the chosen shapes and calculations that were made to determine a total cross-sectional area of 1703.1 in^{2}..

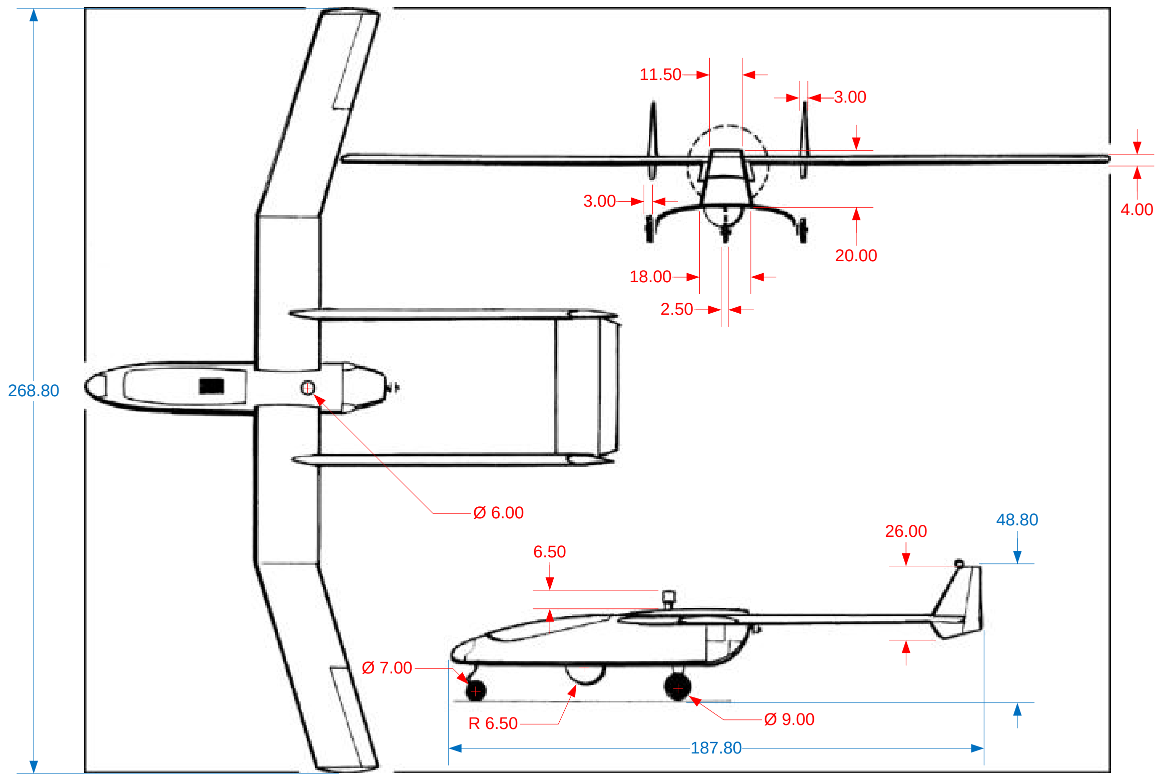


Figure 81 - Shadow 600 Scale Drawing (IHS Global Limited 2010)

Table 45 - Shadow 600 Cross-Sectional Area Calculations

Shadow 600 Component	Approximate Cross-Section Shape	Dimensions (in)			Area (in^2)
Fuselage	Trapezoid	B1	B2	H	295.0
		18.0	11.5	20.0	
Wing	Rectangle	W	H		1075.2
		268.8	4.0		
Tail	2 x Rectangle	W	H		156.0
		3.0	26.0		
Sensor	Semi-Circle	R			66.4
		6.5			
Nose Wheel	Rectangle	W	H		17.5
		2.5	7.0		
Rear Wheel	2 x Rectangle	W	H		54.0
		3.0	9.0		
Antenna	Rectangle	W	H		39.0
		6.0	6.5		
Total Cross-Sectional Area					1703.1

Finally, the percent increase in cross-sectional area was calculated for each weapon system load. The results are assumed to be equal to the percent increase in the drag coefficient, and they are presented in Table 46.

Table 46 - Shadow 600 Cross-Sectional Area Increase with Weapons

Weapon	Single Weapon Increase	Maximum Round Increase
Bomb	3.46%	6.92%
GB-1	1.05%	3.14%
GB-2	3.46%	6.92%
M-1	3.46%	3.46%
M-2	2.44%	2.44%
M-3	1.05%	1.05%
M-4	0.70%	2.80%
M-5	0.89%	8.92%

a) Time on Station

To assess the time on station impact, it was assumed that the total endurance time was equal to the time on station. This assumption was made because the scenario definitions only placed the ground control station 5 km away from the target area. This distance could be covered in less than 3 minutes at 65 knots and meant that the UAV was essentially on station from launch. Endurance time was maximized by being at loiter velocity, so the impact assessment assumed that the UAV would burn fuel at maximum velocity and then transition to loiter once sufficient fuel weight was lost. Under the assumptions of the analysis, the baseline system was capable of a maximum time on station of 365.3 minutes by flying at loiter velocity the entire time, and at maximum velocity the baseline system could fly for 237.3 minutes at 2000 feet. Table 47 shows the time on station and the percent reduction from the baseline 365.3 minutes for each of the weight and drag combinations created by the candidate weapon systems.

Table 47 - Maximum Time on Station for 2,000 feet

Weapon	Quantity	Weight (lbs)	Additional Drag	Time on Station (min)	Percent Reduction
Bomb	1	30	3.46%	311.6	14.67%
Bomb	2	50	6.92%	271.1	25.75%
GB-1	1	26	1.05%	328.9	9.92%
GB-1	3	58	3.14%	280.6	23.15%
GB-2	1	30	3.46%	311.6	14.67%
GB-2	2	50	6.92%	271.1	25.75%
M-1	1	62	3.46%	274.3	24.88%
M-2	1	56.2	2.44%	286.2	21.60%
M-3	1	56	1.05%	293.9	19.51%
M-4	1	20.6	0.70%	337.1	7.68%
M-4	4	52.4	2.80%	288.9	20.88%
M-5	1	14.4	0.89%	343.3	5.98%
M-5	10	54	8.92%	256.9	29.63%

As the table shows, there is configuration that achieves an impact of less than 5 percent reduction in time on station. The primary reason for the significant reduction in endurance time is that it is necessary to fly at a higher throttle setting in order to reduce UAV weight to a point at which level flight becomes possible at the loiter throttle setting. The analysis only considered flying at maximum velocity before transitioning to loiter because maximum velocity was the only velocity possible, initially, for the heavier weapon systems.

b) Maximum Range

While endurance time is of great importance to surveillance UAVs, so is the amount of distance that can be covered over that endurance time. The distance covered by the Shadow 600 was calculated based on the velocity over time data. The MATLAB model calculated the data at 1 minute intervals over 360 minutes. The following tables show the calculated cumulative distance that could be covered by the Shadow 600 in 6 hours or until the fuel ran out for the selected weapon system configurations. The first table assumes that maximum velocity is maintained over the entire flight. At maximum

velocity the baseline Shadow could cover 417.9 nautical miles. The second table assumes that the transition to loiter velocity is made once sufficient fuel has burned off. At loiter velocity, the baseline Shadow could cover 463.9 nautical miles in 360 minutes.

Table 48 – Total Distance at Maximum Velocity at 2,000 feet

Weapon	Quantity	Weight (lbs)	Additional Drag	Total Distance (Nmi)	Percent Reduction
Bomb	1	30	3.46%	404.9	3.12%
Bomb	2	50	6.92%	392.6	6.06%
GB-1	1	26	1.05%	411.8	1.46%
GB-1	3	58	3.14%	401.3	3.97%
GB-2	1	30	3.46%	404.9	3.12%
GB-2	2	50	6.92%	392.6	6.06%
M-1	1	62	3.46%	399.8	4.34%
M-2	1	56.2	2.44%	403.5	3.44%
M-3	1	56	1.05%	407.4	2.52%
M-4	1	20.6	0.70%	413.5	1.07%
M-4	4	52.4	2.80%	403.2	3.53%
M-5	1	14.4	0.89%	413.8	0.99%
M-5	10	54	8.92%	386.6	7.49%

Table 49 - Total Distance for Transition to Loiter Velocity at 2,000 feet

Weapon	Quantity	Weight (lbs)	Additional Drag	Total Distance (NM)	Percent Reduction
Bomb	1	30	3.46%	434.8	6.27%
Bomb	2	50	6.92%	407.3	12.19%
GB-1	1	26	1.05%	443.5	4.40%
GB-1	3	58	3.14%	414.5	10.65%
GB-2	1	30	3.46%	434.8	6.27%
GB-2	2	50	6.92%	407.3	12.19%
M-1	1	62	3.46%	409.9	11.63%
M-2	1	56.2	2.44%	417.6	9.97%
M-3	1	56	1.05%	421.0	9.24%
M-4	1	20.6	0.70%	447.5	3.53%
M-4	4	52.4	2.80%	419.8	9.50%
M-5	1	14.4	0.89%	451.7	2.64%
M-5	10	54	8.92%	394.1	15.05%

For the most part, the impact to maximum range at maximum velocity is within the 5 percent margin, but the opposite is true when a transition to loiter velocity is made.

c) Maximum Velocity

Finally the impact on the full fuel maximum velocity was assessed. The baseline Shadow 600 was capable of 104 knots. For the purposes of this analysis, it was assumed that this was the full fuel maximum velocity at all altitudes. The results for the candidate weapon system are shown in Table 50.

Table 50 - Maximum Velocity at 2,000 feet

Weapon	Quantity	Weight (lbs)	Additional Drag	Full Fuel Maximum Velocity (kts)	Percent Reduction
Bomb	1	30	3.46%	100.3	3.58%
Bomb	2	50	6.92%	96.7	7.02%
GB-1	1	26	1.05%	102.2	1.74%
GB-1	3	58	3.14%	99.1	4.73%
GB-2	1	30	3.46%	100.3	3.58%
GB-2	2	50	6.92%	96.7	7.02%
M-1	1	62	3.46%	98.6	5.18%
M-2	1	56.2	2.44%	99.7	4.13%
M-3	1	56	1.05%	100.8	3.10%
M-4	1	20.6	0.70%	102.7	1.27%
M-4	4	52.4	2.80%	99.6	4.20%
M-5	1	14.4	0.89%	102.8	1.15%
M-5	10	54	8.92%	95.0	8.69%

Most of the candidate weapon configurations are within the 5 percent margin for maximum velocity. The systems that fail to meet the margin all have drag increase of at least 3.46 percent. While drag seems to be the most significant factor, the weight also has a noticeable effect. The single Bomb and single GB-2 also experience a 3.46 percent increase in drag, but their lower weight allows them to stay within the threshold, where the heavier M-1 exceeds the 5 percent limit due to its 62 pound weight.

5. Aerodynamic Performance Conclusions

Overall, the addition of a weapon system to a UAV appears to have a significant impact on the on-station time and the range at loiter velocity. The impact is less severe on the maximum velocity and the range at maximum velocity. Lower drag weapon systems perform better than higher drag ones, but there is still a noticeable impact from the weight.

D. OMOE Decision Matrix

The OMOE decision matrix is a graphical tool used to combine the value scores and global weights for each KPP category and alternative weapon to generate total OMOEs. The formula to perform the total OMOE calculation is provided in Equation 34.

Equation 34 - Total OMOE

In this function, *KPP Weight(j)* represents the global weight of a given KPP, and *Alternative KPP Score(j)* is the value score for the KPP for a given alternative. Table 51 is a summary of the individual scoring of each KPP for each weapon alternative, the global weights associated with each measure that were calculated from QFD, and the total OMOE will be calculated using Equation 34.

According to the OMOE scores of each candidate weapon system integrated on the RUINS Tier II UAV, the overall winner based on score alone is M5 with an OMOE score of 0.621, whereas the second highest score is 0.563 and belongs to weapon candidate M4. The team performed a sensitivity analysis to determine whether the assumptions that were made regarding the weighting of the KPPs are valid. Furthermore, cost analysis and integration studies were performed as OMOE alone should not be the only decision driver.

Table 51 – Candidate Weapon OMOE Values

	KPP	Global Weights	Alternatives							
			Bomb	GB1	GB2	M1	M2	M3	M4	M5
UAV Performance & Suscepbitiliy	Weapon Weight	0.020	1.000	1.000	1.000	0.000	1.000	1.000	1.000	1.000
	Maximum Weapon Rounds at Takeoff	0.126	0.200	0.400	0.200	0.000	0.000	0.000	0.600	1.000
	Maximum Weaponized UAV Range	0.070	0.714	0.787	0.714	0.774	0.806	0.838	0.803	0.664
	UAV On-station Time	0.070	0.000	0.009	0.000	0.000	0.069	0.151	0.098	0.000
	Stand-off Range	0.054	0.000	0.000	0.000	0.361	1.000	1.000	1.000	1.000
Weapon Delivery Performance	Minimum Weapon Range	0.135	0.000	0.000	0.000	0.383	0.383	0.593	0.380	0.380
	Maximum Effective Weapon Range	0.135	0.000	0.000	0.044	0.018	0.107	0.064	0.478	0.421
	Weapon Speed	0.075	0.178	0.289	0.361	0.451	0.347	1.000	0.407	1.000
	Weapon Accuracy	0.123	0.000	1.000	1.000	0.000	1.000	0.000	1.000	0.000
Weapon Warhead Performance	Warhead 50% Pk Human	0.096	0.000	0.000	1.000	0.000	0.000	0.000	0.260	1.000
	Warhead 50% Pk Truck	0.096	0.000	0.000	1.000	0.000	0.000	0.000	0.590	1.000
	OMOE Score	1.000	0.109	0.271	0.442	0.162	0.351	0.308	0.563	0.621

E. Sensitivity Analysis

A sensitivity analysis was done for each RUINS KPP. How the categories are weighted can determine whether one weapon is chosen over another. The purpose of performing a sensitivity analysis is to determine whether changing the category weights would alter the results dramatically and change the weapon of choice. The sensitivity analysis is performed by making the weight of a single KPP a one and making the other KPPs zero, thereby generating a new score for each weapon.

Weapon Weight was the first KPP analyzed. The original global weight of this measure and the corresponding score for each weapon was determined and shown in Figure 82. The point of indifference for this KPP was determined to be 0.0681, which is approximately 0.048 different than the global weight of 0.020 for this KPP.

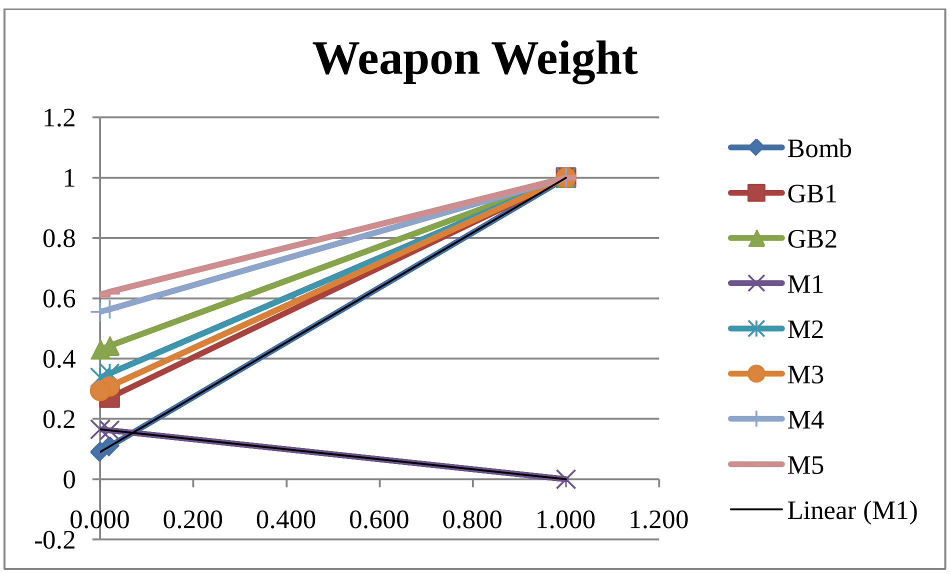


Figure 82 - Weapon Weight Sensitivity

Maximum Rounds at Takeoff was the second KPP analyzed. The original global weight of this measure and the corresponding score for each weapon was determined and shown in Figure 83. The point of indifference for this KPP was determined to be 0.20, which is approximately 0.074 different than the global weight of 0.126 for this KPP.

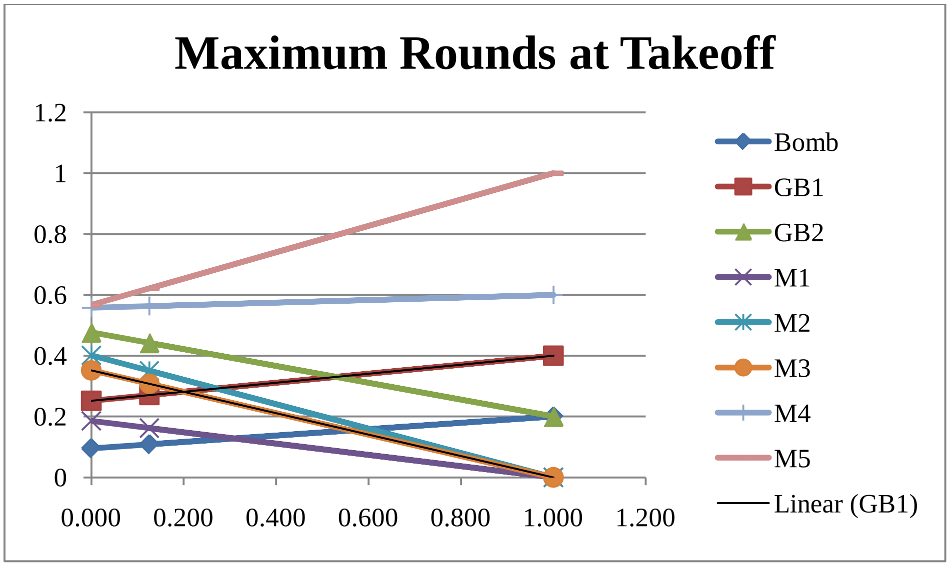


Figure 83 - Maximum Rounds at Takeoff Sensitivity

Maximum Weaponized UAV Range was the third KPP analyzed. The original global weight of this measure and the corresponding score for each weapon was determined and shown in Figure 84. The point of indifference for this KPP was determined to be 0.346, which is approximately 0.276 different than the global weight of 0.070 for this KPP.

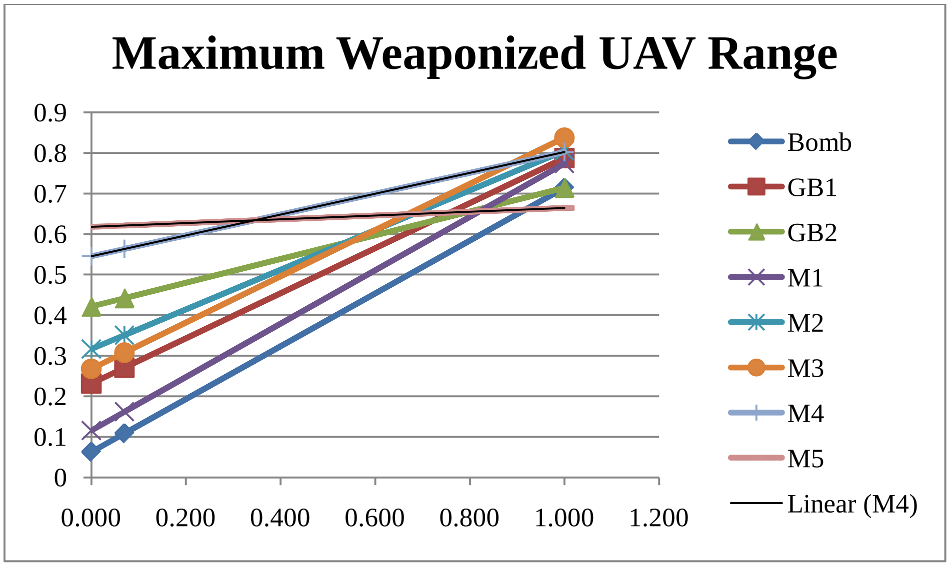


Figure 84 – Maximum Weaponized UAV Range Sensitivity

UAV On-station Time was the fourth KPP analyzed. The original global weight of this measure and the corresponding score for each weapon was determined and shown in Figure 85. The point of indifference for this KPP was determined to be 0.396, which is approximately 0.325 different than the global weight of 0.070 for this KPP.

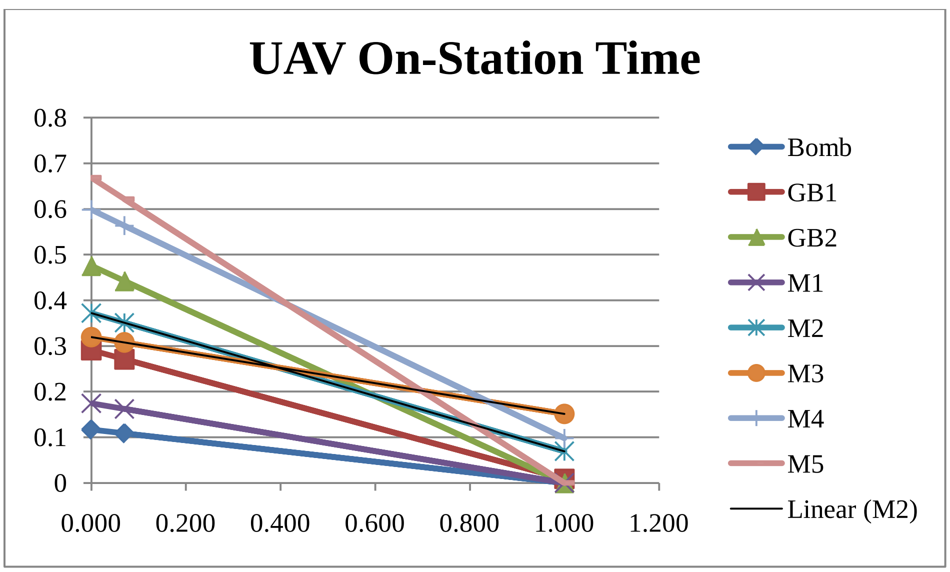


Figure 85 – UAV On-Station Time Sensitivity

Stand-Off Range was the fifth KPP analyzed. The original global weight of this measure and the corresponding score for each weapon was determined and shown in Figure 86. The point of indifference for this KPP was determined to be 0.134, which is approximately 0.079 different than the global weight of 0.054 for this KPP.

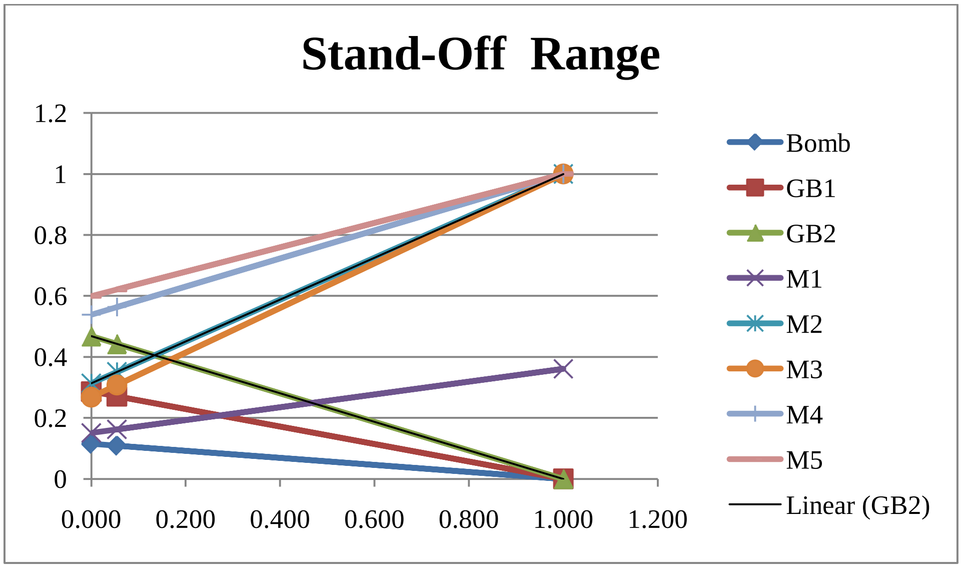


Figure 86 – Stand-Off Range

Minimum Weapon Range was the sixth KPP analyzed. The original global weight of this measure and the corresponding score for each weapon was determined and shown in Figure 87. The point of indifference for this KPP was determined to be 0.281, which is approximately 0.145 different than the global weight of 0.135 for this KPP.

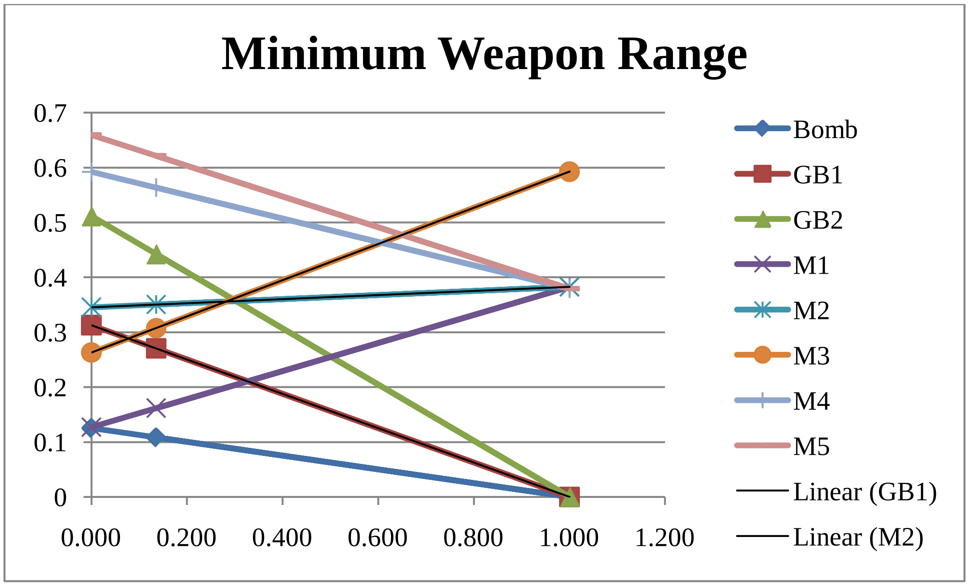


Figure 87 - Minimum Weapon Range Sensitivity

Minimum Weapon Range was the sixth KPP analyzed. The original global weight of this measure and the corresponding score for each weapon was determined and shown in Figure 88. The point of indifference for this KPP was determined to be 0.576, which is approximately 0.440 different than the global weight of 0.135 for this KPP.

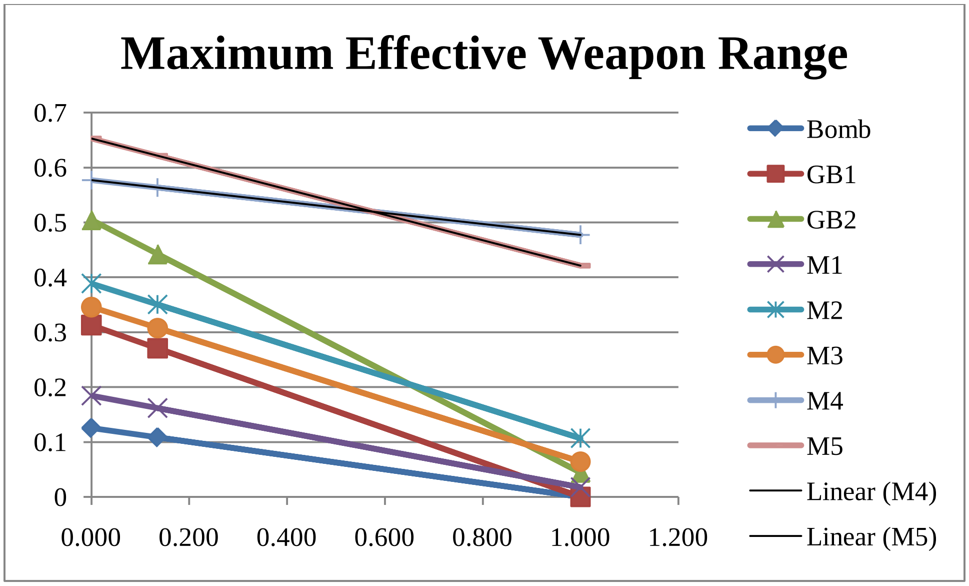


Figure 88 – Maximum Effective Weapon Range Sensitivity

Weapon Speed was the eighth KPP analyzed. The original global weight of this measure, and the corresponding score for each weapon, was determined and shown in Figure 89. The first point of indifference for this KPP is 0.025, which is approximately -0.418 different than the global weight of 0.075 for this KPP. The second point of indifference for this KPP was determined to be 0.133, which is approximately 0.058 different than the global weight of 0.075 for this KPP.

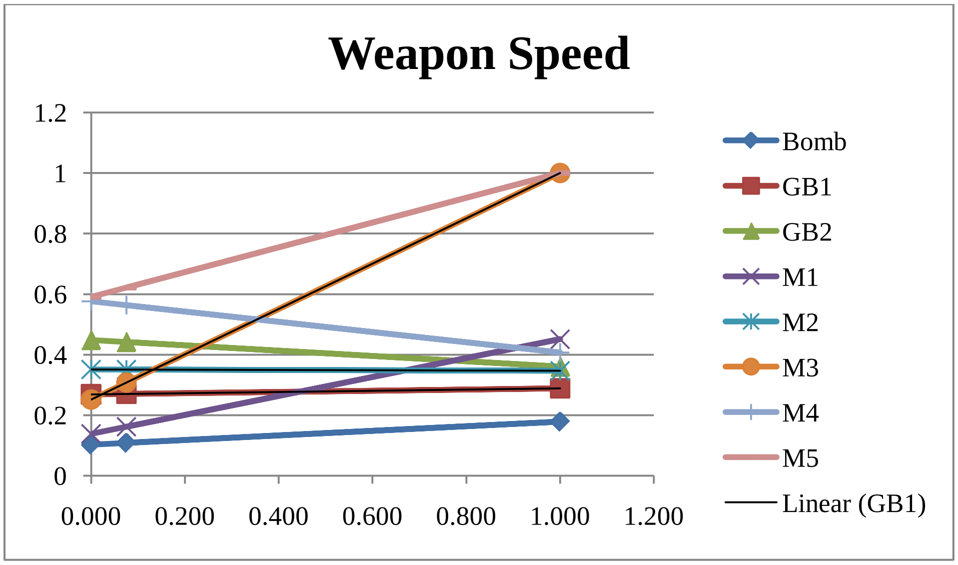


Figure 89 – Weapon Speed Sensitivity

Weapon Accuracy was the ninth KPP analyzed. The original global weight of this measure and the corresponding score for each weapon was determined and shown in Figure 90. The first point of indifference for this KPP is 0.083, which is approximately -0.039 different than the global weight of 0.123 for this KPP. The second point of indifference for this KPP was determined to be 0.154, which is approximately 0.031 different than the global weight of 0.123 for this KPP.

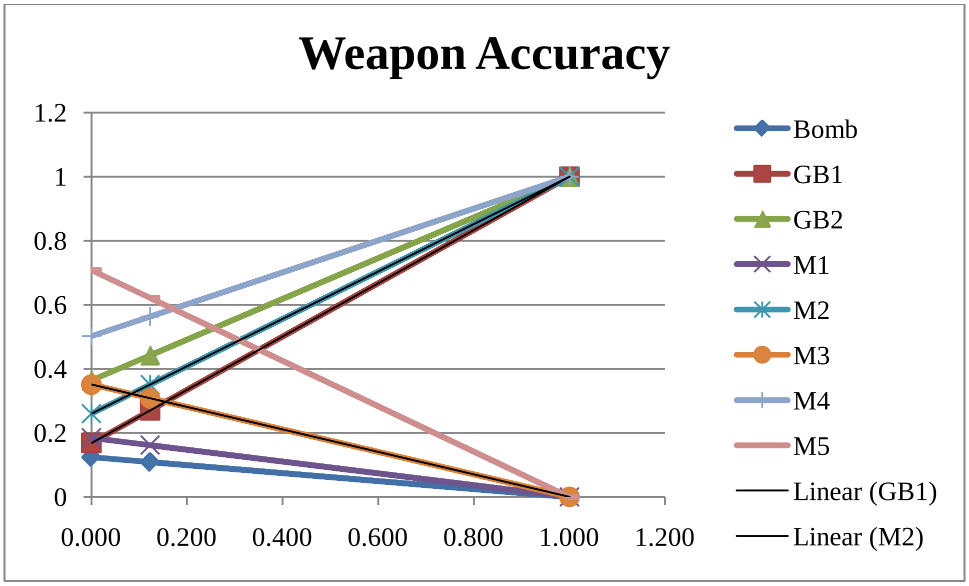


Figure 90 – Weapon Accuracy Sensitivity

Warhead 50 Percent P_K Range Human was the tenth KPP analyzed. The original global weight of this measure and the corresponding score for each weapon was determined and shown in Figure 91. The point of indifference for this KPP was determined to be 0.223, which is approximately 0.127 different than the global weight of 0.096 for this KPP.

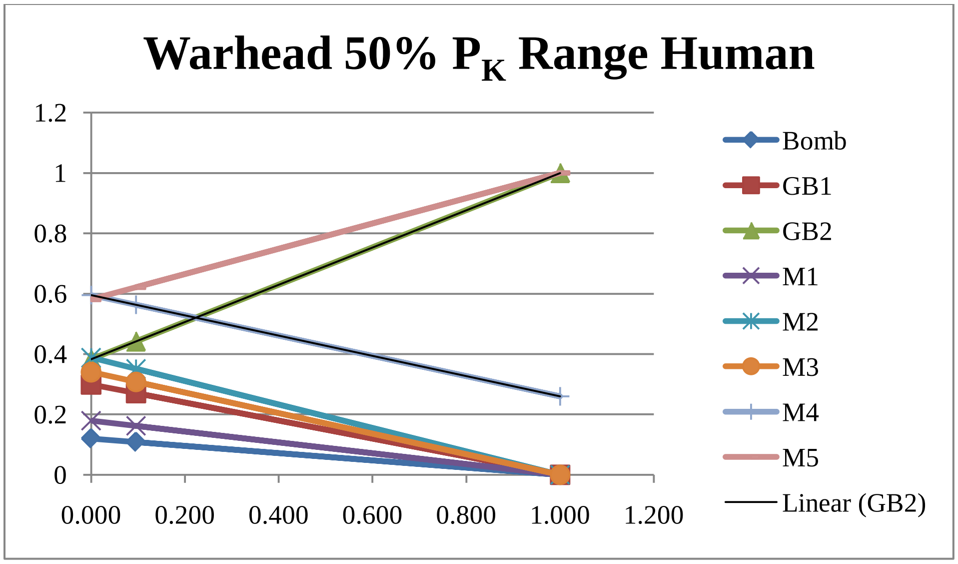


Figure 91 - Warhead 50% P_K Range Human Sensitivity

Warhead 50% P_K Range Truck was the eleventh KPP analyzed. The original global weight of this measure and the corresponding score for each weapon was determined and shown in Figure 92. The point of indifference for this KPP was determined to be 0.302, which is approximately 0.206 different than the global weight of 0.096 for this KPP.

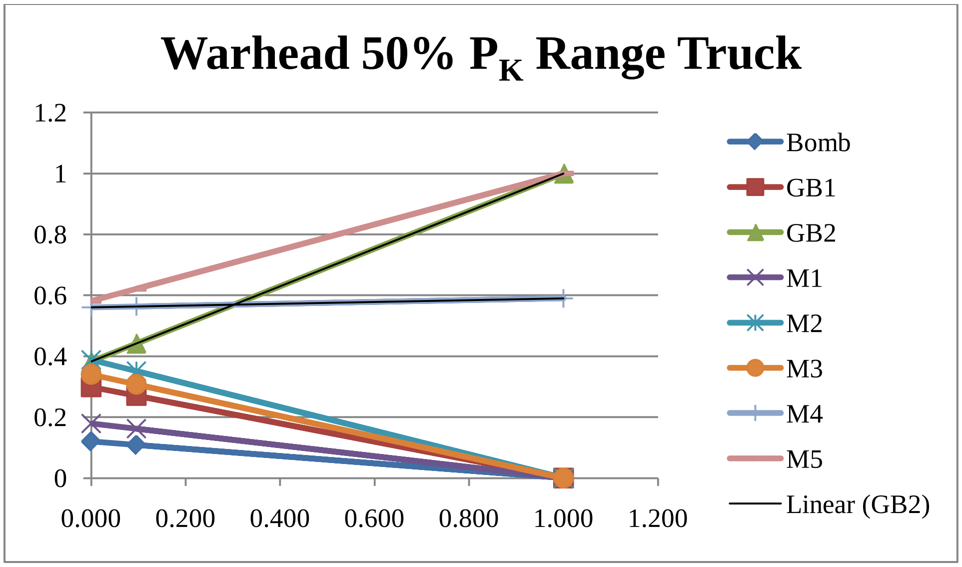


Figure 92 – Warhead 50% P_K Range Truck Sensitivity

A KPP is considered not sensitive if the point of indifference is greater than the global weight plus 10 percent of itself. In this analysis all of the KPPs were found to be not sensitive. The results of the sensitivity analyses performed on each KPP have determined that the RUINS KPPs are not sensitive and are shown in Table 52. This indicates that the assumptions that were made regarding the weighting of the KPPs are reasonable. Adjustments to the RUINS KPP weights will not change the study. Therefore, we are confident that our recommendations will be correct.

Table 52 – KPP Sensitivity Summary

Impact Category	KPP	Point of Indifference	KPP Weight -/+ 10% KPP Weight	Sensitive
UAV Performance & Susceptibility	Weapon Weight	0.0681	0.022	No
	Maximum Rounds at Takeoff	0.2	0.139	No
	Maximum Weaponized UAV Range	0.346	0.077	No
	UAV On Station Time	0.396	0.077	No
	Stand-Off Range	0.134	0.060	No
Weapon Delivery Performance	Minimum Weapon Range	0.078 0.281	0.122 0.149	No
	Maximum Effective Weapon Range	0.576	0.149	No
	Weapon Speed	0.025 0.133	0.068 0.083	No
	Weapon Accuracy	1.00 0.154	0.110 0.135	No
Weapon Warhead Effectiveness	Warhead 50% P_K Range Human	0.223	0.105	No
	Warhead 50% P_K Range Truck	0.302	0.105	No

F. Cost Analysis

As one of the three main pillars of program management, cost is one of the most important considerations in the development of any new weapon system. Not only must a new weapon system meet performance and schedule requirements, but it must do both of these within the constraints of a budget. In order to ensure the successful fielding of a new weapon system such as RUINS, a Cost Analysis was conducted to take an early look at some of the costs associated with the proposed alternative design solutions.

1. Cost Model Description

The cost model for RUINS consisted of a combination of the Analogy and Parametric Methods, relying mostly on historical data from similar systems as the source

of cost data. Historical information provided a source for unit costs and a basis for estimating the number of units required and hardware upgrades. Although the overall system cost will ultimately depend largely on the number of weapons needed to combat the threat, the historical data provides a basis for estimating quantity requirements. In the development of the RUINS cost model, every task was treated as a cost-risk analysis and uncertainty was recognized as an inherent part of every estimate.

2. Cost Analysis Approach and Methodology

Since RUINS builds heavily on pre-existing platforms and technology, the scope of the cost estimation only included those parts of the overall system that were developed specifically for RUINS. UAV platform and sensor costs were considered out of scope for the cost analysis. The primary focus of the cost analysis centered around the cost of the RUINS weapon and the integration estimates.

In essence, RUINS is an upgrade to an existing UAV platform that comes with unavoidable performance costs to the UAV. UAV performance effects were modeled as a part of the RUINS performance analysis, but UAV Life Cycle Costs were considered equal, since all feasible RUINS alternatives used the same surrogate UAV platform. UAS Life Cycle costs were researched as a part of the overall cost analysis research effort, however, many small UAS, like those utilized by RUINS, are still owned by private companies whose cost information is considered proprietary.

As the scope of the RUINS engineering analysis focused largely on the feasibility of arming a small UAV, the surrogate UAV and sensor were assumed to be mature technologies with established support infrastructures. By leveraging the existing technologies for the UAV and sensor, many of the associated support costs could be assumed by the existing infrastructure provided within the DoD.

Based on the RUINS Problem Definition phase and System Engineering Analysis, certain cost-drivers emerged as areas that would most likely become deciding factors in the analysis of alternatives. The following areas were quickly identified as candidate cost-drivers for RUINS:

- Weapon Weight

- Maximum Rounds
- Engagement Range
- Guidance Type
- Warhead Weight

In addition to the above cost-drivers, the development cost of RUINS will depend highly on the successful integration of a weapon system on a Tier I or Tier II UAV. Because lethal weapons have yet to be fielded on these smaller tiers of UAVs, there is a great degree of uncertainty when it comes to the cost of system integration. Although the surrogate UAV, the sensor, and the weapon are all existing and mature technologies, they were not designed to be used together on one system. Overall, system integration cost poses the greatest risk as a cost driver for RUINS.

In the process of developing an accurate cost estimate for RUINS, it was necessary to address the proposed operational and support concepts. RUINS is designed to be a tactically launched UAV, operated and maintained at the unit level. At the Unit level, RUINS units will require several air vehicles, enough ground stations to control the air vehicles, and enough personnel to operate and maintain all components of the system. To support the system, the RUINS units will require appropriate storage containers, portable operations spaces and enough spare parts to ensure mission accomplishment. At some point during the life cycle of RUINS, a hardware refresh will be needed to keep the system ahead of evolving threats and to allow RUINS to continue to be an effective weapon system until the end of the system life cycle

Quantity requirements for RUINS depend highly on the operational tempo anticipated for the life of the system as foreseen during development. Overall force requirements are determined by strategic objectives and detailed threat assessments and were not considered within the scope of this project. The cost estimation effort was based largely on a historical analogy of similar system purchase quantities.

3. Cost Data

RUINS cost research focused primarily on the cost of the munitions for the surrogate UAV and the cost of integrating a new weapon on an existing airframe.

Weapon unit cost information was found in a variety of sources including IHS Jane's Databases and online articles. Inflation indices were drawn from the Naval Center for Cost Analysis (NCCA) and current government Discount Rates were obtained from the 2010 Office of Management and Budget (OMB) Circular A-94, Appendix C.

a) Bomb Data

The RUINS Bomb was modeled as a theoretical 10-lb gravity bomb: therefore, there was no historical cost data that directly correlated to its cost. Instead, the theoretical cost of the Bomb was derived from the cost of the Mk-82 and Mk-84 Gravity Bombs, munitions used by various U.S. platforms. According to the Federation of American Scientists (FAS), the Mk-82, 500-lb bomb, cost approximately $287 (Federation of American Scientists 2000), while the Mk-84, 2,000-lb bomb, cost approximately $3,100 as of FY2000 (Federation of American Scientists 2000).

b) GB-1 Data

The RUINS GB-1 was modeled on ATK's G2M. Although the RUINS GB-1 was included as a candidate weapon for RUINS, the G2M is very early in the development stage and no cost data could be found on which to base a cost estimate. The G2M is a GPS Guided Munition so can be compared to a dumb bomb with a Joint Direct Attack Munition (JDAM) kit added to it, JDAM being a kit that allows dumb bombs to be GPS/INS guided. To determine the total unit cost of a G2M, the estimated cost of a six pound bomb was calculated and added to the unit cost of a JDAM kit. IHS online databases provided procurement costs on which the JDAM kits cost estimate was based. According to IHS online databases, contracts were awarded to Boeing in 2006 for 12,889 JDAM kits, 2008 for 4,372 JDAM kits and 2009 for 2925 JDAM kits estimated at 296, 107 and 72 million dollars respectively (IHS Global Limited 2010).

c) GB-2 Data

The RUINS GB-2 was modeled after Textron Defense Systems' Selectively Targeted Skeet weapon. IHS Jane's online databases provided procurement costs on which to base a cost estimate for the GB-2. According to IHS Jane's online databases, a contract for 332 Sensor Fuzed Weapons (the weapon package that includes STS submunitions) was awarded in January 2006 for approximately $108.1 million (IHS

Global Limited 2010). In addition, India is in negotiations to purchase 533 CBU-105s (4 STS per CBU-105) at an estimated $375 million (IHS Global Limited 2010).

d) M-1 Data

Since the RUINS M-1 missile was modeled after Lockheed Martin's Javelin Missile, cost data for the M-1 missile was estimated based on historical costs of the Javelin Missile. IHS Jane's online databases provided the historical cost data for the Javelin Missile, including U.S. Army procurements between FY 2003 and FY 2010. U.S. Army Javelin Missile lot quantities and cost data are shown in Table 53. In FY2006, the U.S. Army purchased a block upgrade of the Javelin Missile from Block 0 to Block 1. The Army retrofitted 450 missiles in FY 2006 and 349 missiles in FY 2007 for $13.8 million and $10.4 million respectively (IHS Global Limited 2010).

Table 53 - U.S. Army Javelin Missile Procurements (IHS Global Limited 2010)

	Fiscal Year							
	2003	2004	2005	2006	2007	2008	2009	2010
Volume (units)	1,478	991	1,038	300	250	1,320	1,320	1,265
Value (USD)	101,280	75,649	79,941	23,691	33,125	146,798	166,816	163,627

e) M-2 Data

The RUINS M-2 missile was modeled based on Rafael Armament Development Authority's Spike MR/LR anti-tank weapon system. Cost estimates for the M-2 missile were derived from research data found in IHS Jane's online databases. According to Jane's online databases, the Netherlands Ministry of Defense purchased 2,400 Spike MR/LR missiles at a reported $225 million (IHS Global Limited 2010).

f) M-3 Data

General Dynamics Corporation's FIM-92 Stinger missile served as the basis for modeling the RUINS M-3 missile. Historical Stinger procurement information found in IHS Jane's online databases provided the necessary cost data needed to make a cost estimate of the RUINS M-3 missile. In 1987, the U.S. Army Missile Command contracted Raytheon Missile Systems Division for 400 FIM-92 missiles at an estimated

$24.6 million (IHS Global Limited 2010). Additionally, the Army exercised an option for an additional 1,500 missiles in 1989 for $54.4 million (IHS Global Limited 2010).

g) M-4 Data

The RUINS M-4 missile was modeled based on the NAVAIR Spike missile, currently in development by NAWCWD, China Lake. Although there are no procurement cost numbers available, the expected cost of the NAVAIR Spike missile was reported as $4,000 per unit as of 2003 (Selinger 2003) and $5,000 per unit as of 2008 (Mathews 2008). The expected costs per unit for the NAVAIR Spike missile served as the basis for the cost estimate for the RUINS M-4 missile.

h) M-5 Data

The AeroVironment Switchblade served as the basis for the RUINS M-5 missile. Although the system has no procurement costs as it is still in development, online sources report that the new weapon will cost at least $30,000 per unit (Strategy World 2010).

4. Cost Assumptions

As the RUINS alternatives are theoretical munitions based on several different real world weapons, certain assumptions were made in order to derive meaningful RUINS costs from the reference weapons. Specific assumptions were made in order to estimate average unit costs, Net Present Values (NPVs), and benefit scores. Specific RUINS weapon integration costs were based on assumptions drawn from integration cost research.

a) Average Unit Cost Assumptions

Since the 10-lb gravity bomb is a theoretical weapon, there are no cost references for an actual 10-lb munition. In order to derive a theoretical average unit cost for the Bomb, a unit cost-to-weight ratio was established based on the Mk-82, 500-lb bomb, and the Mk-84, 2,000-lb bomb. The Mk-82 and Mk-84 were used to develop the ratio as they are much heavier gravity bombs that are analogous to the RUINS Bomb. Based on the cost-to-weight ratio for the Mk-82 and Mk-84, the average unit cost of the RUINS Bomb was derived.

Because ATK's G2M is so early in development, there are no specific cost references available on which to base the GB-1 estimate. In an effort to make a

reasonable cost estimate of the GB-1, an upgrade cost-to-unit cost was established based on the JDAM upgrade for a six pound bomb based on the cost-to-weight ratio derived from the Mk-82 and Mk-84 bombs. The JDAM upgrade for standard gravity bombs was established as an analogous upgrade for the RUINS Bomb to be upgraded to a GB-1. Based on the upgrade ratio, it was possible to estimate the average unit cost for the GB-1.

The Javelin cost research revealed that there were two different Blocks of hardware and correlating differences in unit costs (IHS Global Limited 2010). In order to avoid unit cost differences caused by the different Block upgrades, only the Block 1 unit costs were used in the calculation of the overall average unit cost for the M-1.

Research for the RUINS M-2 cost estimate is based on a reference for Spike MR/LR system cost that includes the cost of launching posts in addition to the submunition (IHS Global Limited 2010). In order to account for the added cost of the launching hardware, the Spike MR/LR purchase quantities were reduced by 100 units.

M-3 cost research is based on FIM-92 Stinger unit costs that are a few decades old (IHS Global Limited 2010). Although it is possible to account for the inflated value, it is not likely that current Stinger inventory is the exact same hardware that was bought in the referenced procurement. Although the reference unit cost data is old, the M-3 cost estimate does not take into account any upgrades to the system since the cost reference from the late 1980's.

b) Net Present Value Assumptions

As a means to calculating NPVs for each of the RUINS munitions, it was necessary to make some specific assumptions about the RUINS program including number of years of procurement, quantities procured, integration costs and hardware upgrades. For all RUINS NPV calculations, the average cost per unit and upgrade costs were converted into then-year dollars, as necessary, using inflation indices provided by the Naval Center for Cost Analysis (Naval Center for Cost Analysis 2010) based on the expected procurement year. For NPV comparisons, all then-year dollars were converted into FY 2011 dollars using discount rates provided in the OMB Circular A-94, Appendix C (Office of Management and Budget 2010).

As a basis for NPV calculations, it was necessary to estimate the expected life cycle duration of RUINS procurements. Based on the sum of the research for all of the RUINS weapons, the RUINS program was assumed to have a life cycle similar to some of those weapons: 10 years. The RUINS system was assumed to start its procurement cycle in FY 2014 as a way of accounting for the time needed for system development. Thus the RUINS costs were calculated from FY 2014 through FY 2023.

RUINS integration costs were assumed to be incurred during the first year of the RUINS life cycle since most integration efforts would be complete prior to the deployment of the system or subsequent procurements.

During the life cycle of RUINS, a hardware upgrade was planned for the fifth year of the program, roughly the halfway point. The hardware upgrade was based on research information from the Javelin system, whose Block 1 upgrade also occurred at about the mid-way point of procurement (IHS Global Limited 2010). Based on a ratio of the Javelin Block 1 upgrade cost to overall procurement cost, an upgrade cost for each of the RUINS weapons was calculated.

Annual procurement quantities for the RUINS weapons were based on the historical procurement quantities for the Javelin Missile system. Similar to the pattern of procurements for the Javelin Missile system, the pattern of procurement quantities repeats following the hardware upgrade (IHS Global Limited 2010). Although the maximum number of stored rounds was not equal for each of the RUINS munitions, the annual procurement quantities for each of the RUINS weapons were assumed to be equal.

5. Integration Cost Assumptions

Since RUINS depends heavily on the integration of systems already fielded or in development, the cost of system integration becomes a major issue for cost analysis. Cost data for system integration of existing systems proved extremely difficult to locate. Through research, it was found that many currently fielded systems kept no record of the cost of system integration, but there were some accepted methods for estimating costs associated with UAS.

With the increasing number of aircraft in inventory, every added requirement can bring a significant cost increase. "From 2002 through 2008, the number of unmanned aircraft in the Department of Defense's (DoD) inventory increased from 167 to more than 6,000 in an effort to meet growing warfighter demand for these capabilities in Iraq and Afghanistan" (GAO 2009). Cost can determine what changes can be made to an aircraft because every change has a cost associated it with it. One example of this is the Global Hawk, which is an unmanned aerial vehicle used by United States Air Force and Navy. "On April 13, 2005, the Acting Secretary of the Air Force formally notified Congress that the procurement unit cost of the Global Hawk had increased 18 percent over the baseline estimate" (GAO 2005). The reasons for the cost increase were requirements growth, increased sensor cost, deferred aircraft purchases, increased cost of airframe, increased support requirements and initial spares and increased government costs for acceptance tests, design changes and mission support" (GAO 2005). Changes can have a cost snowball effect. A new sensor must be tested, which has a cost has associated with it. One added sensor can correlate to added weight, therefore the airframe now has to compensate. Sensors, like all equipment have to be replaceable in case of a failure. As a result, spares have to be available. All of the additional costs multiplied by the number of fielded systems can endanger the viability of an acquisition program. This has to be taken into account when considering all options to aid the coalition forces with the counter improvised explosive device effort.

> *Empty weight cost is a commonly used metric in the aviation industry because it tends to remain constant across a variety of aircraft types. That number today is roughly $1500 per pound. The empty weight and cost data for DoD UA is depicted in Figure 4-1. It shows current DoD UA platforms cost approximately $1,500 per pound of empty weight and $8,000 per pound of payload capacity as one "cost per capability" metric (Office of the Secretary of Defense 2005).*

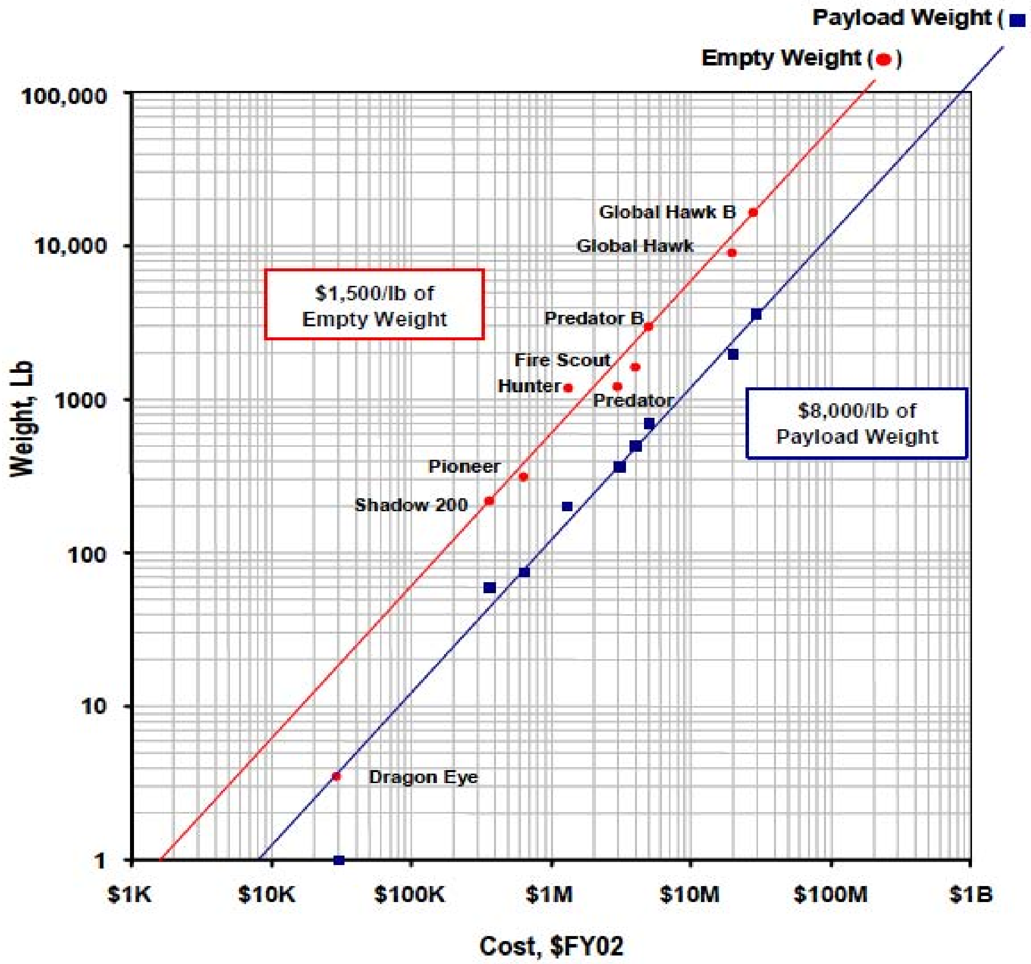


Figure 93 - UAV Weight vs. Cost from (Office of the Secretary of Defense 2005)

Taking the estimates from above and looking at possible EO/IR sensors in Figure 93, the cost of adding a sensor can range dramatically. This can be seen when comparing the cost of adding a 35-lb vs. 186-lb sensor. The estimated cost per aircraft was $280,000 for the 35-lb sensor and $1,488,000 for the 186-lb sensor. This difference was substantial, especially when the cost was multiplied by the number of aircraft that would house the sensor. This is why it was necessary to evaluate all alternatives, when adding capabilities, in order to obtain the best "bang for the buck."

6. Cost Model Development

In developing the RUINS cost model, estimates were generated for candidate weapon integration costs, average unit costs, and NPV.

a) Integration Costs

Integration costs for each of the candidate weapons were based on the assumption that integration of the candidate weapon would be directly proportional to the overall weight of the candidate weapon system being added to the UAV. The weapon integration cost ratio was $8,000 per pound of payload (Office of the Secretary of Defense 2005). Since the reference for the integration cost ratio was from 2005, the integration cost for each candidate weapon was calculated in FY 2005 dollars and translated to FY 2011 dollars using the NCCA Raw Inflation Index. Estimated integration costs for each of the RUINS candidate weapons are shown in Table 54 and a comparison of each candidate weapons' estimated integration cost is shown in Figure 94.

Table 54 - Candidate Weapon Integration Costs

Weapon	Total Payload (lbs)	Estimated Integration Cost (FY05$k)	Estimated Integration Cost (FY11$k)
Bomb	75.0	600.00	673.58
GB-1	67.0	536.00	601.73
GB-2	75.0	600.00	673.58
M-1	87.0	696.00	781.35
M-2	81.2	649.60	729.26
M-3	81.0	648.00	727.47
M-4	77.4	619.20	695.13
M-5	79.0	632.00	709.50

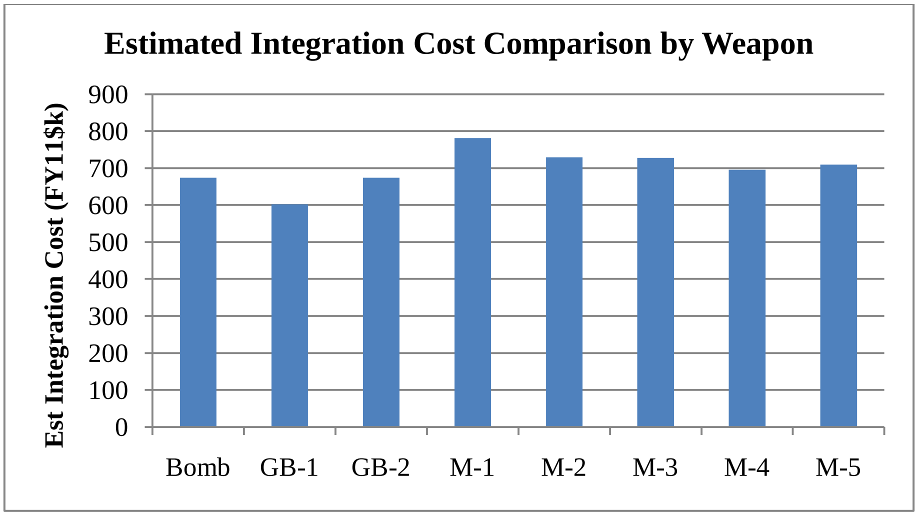


Figure 94 - Estimated Integration Cost Comparison by Weapon

In order to calculate procurement costs, an overall Average Unit Cost was derived from research data for each of the RUINS candidate weapons. Each of the cost references were translated into an average unit cost by dividing the procurement cost by the number of units procured. Each of the average unit costs were assigned a fiscal year based on the citation. All respective then-year dollars were converted into FY 2011 dollars as a basis for comparison. For candidate weapons with more than one cost reference, the FY 2011 average unit costs for each reference were averaged into an overall average unit cost for that weapon. Overall average unit costs are contained in Table 55.

Table 55 - Overall Average Unit Costs

Weapon	Overall Average Unit Cost (FY11$k)
Bomb	0.01
GB-1	25.15
GB-2	135.39
M-1	128.83
M-2	112.35
M-3	70.50
M-4	4.94
M-5	30.33

(1) Annual Cost Data. For all RUINS annual cost calculations, the average cost per unit and upgrade costs were converted into then-year dollars as necessary using inflation indices provided by the Naval Center for Cost Analysis (Naval Center for Cost Analysis 2010) based on the expected procurement year. Based on the sum of the research for all of the RUINS weapons, the RUINS program was assumed to have a life cycle similar to some of those weapons: 10 years. The integration costs will occur in the beginning as the integration efforts would be complete prior to the deployment of the system subsequent procurements. At the half way point, 5 years, a hardware upgrade will occur. The upgrade timeframe was based on research information from the Javelin system, whose Block 1 upgrade occurred at about the mid-way point of procurement (IHS Global Limited 2010). The RUINS system was assumed to start its procurement cycle in FY 2014 as a way of accounting for the time needed for system development. Thus the RUINS costs were calculated from FY 2014 through FY 2023. The annual cost results for each of the RUINS munitions can be seen below in Figure 95 through Figure 102.

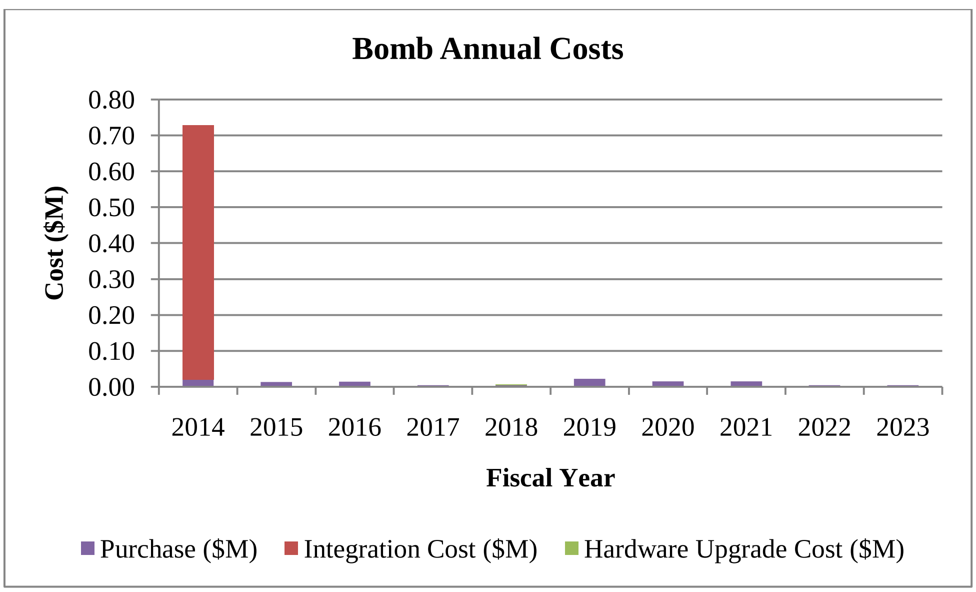


Figure 95 - Bomb Annual Costs

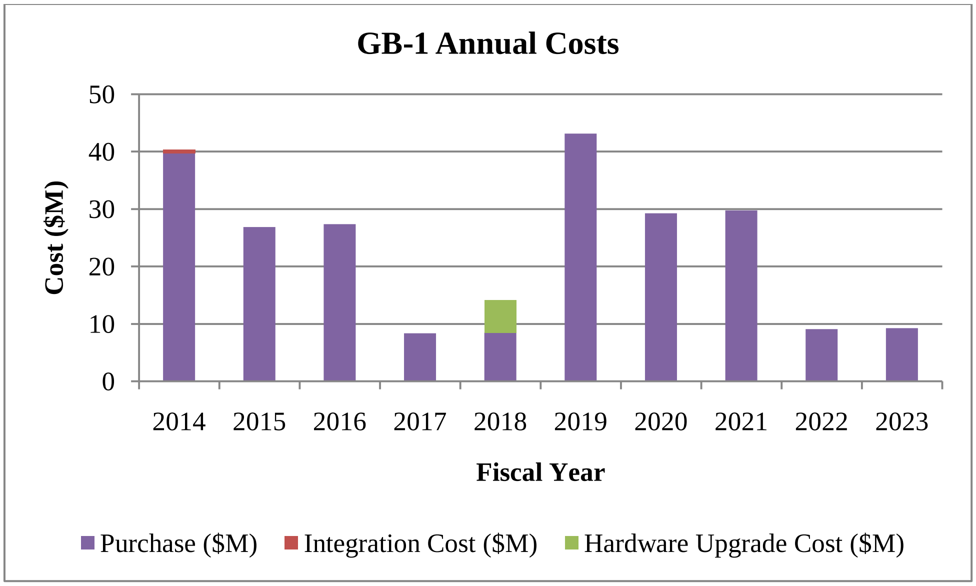


Figure 96 - GB-1 Annual Costs

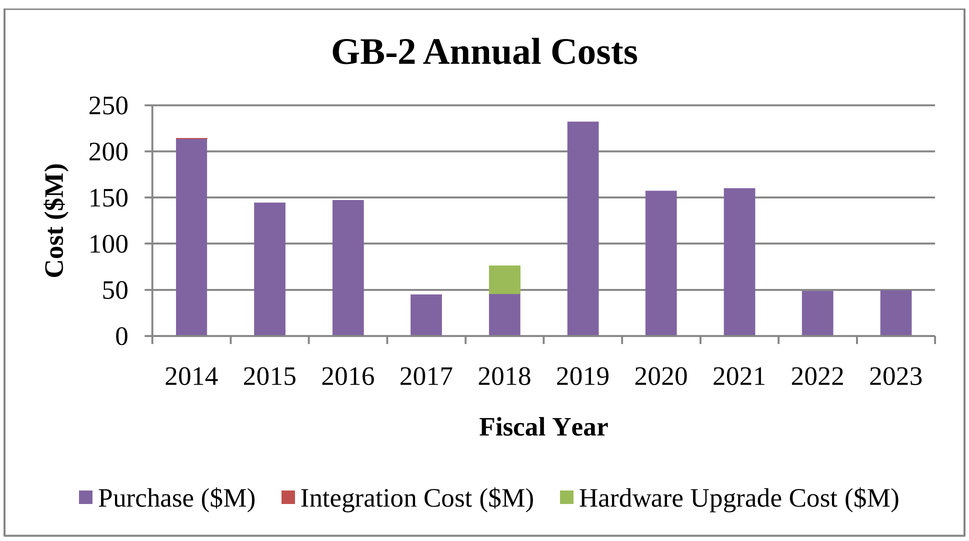


Figure 97 - GB-2 Annual Costs

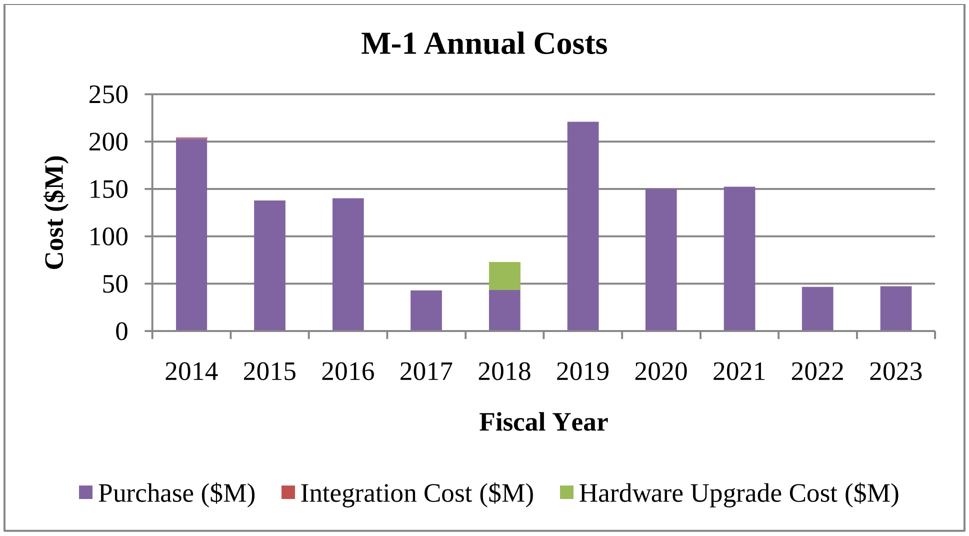


Figure 98 - M-1 Annual Costs

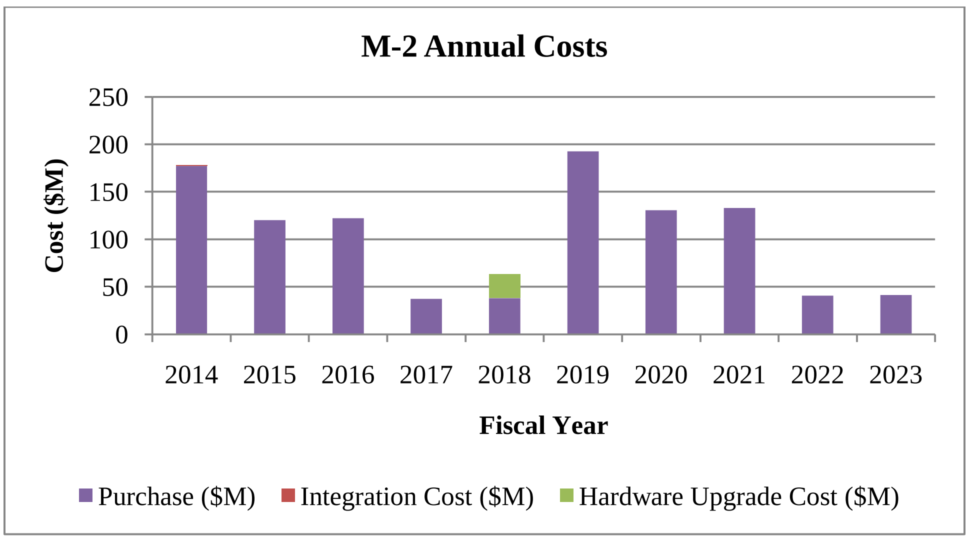


Figure 99 - M-2 Annual Costs

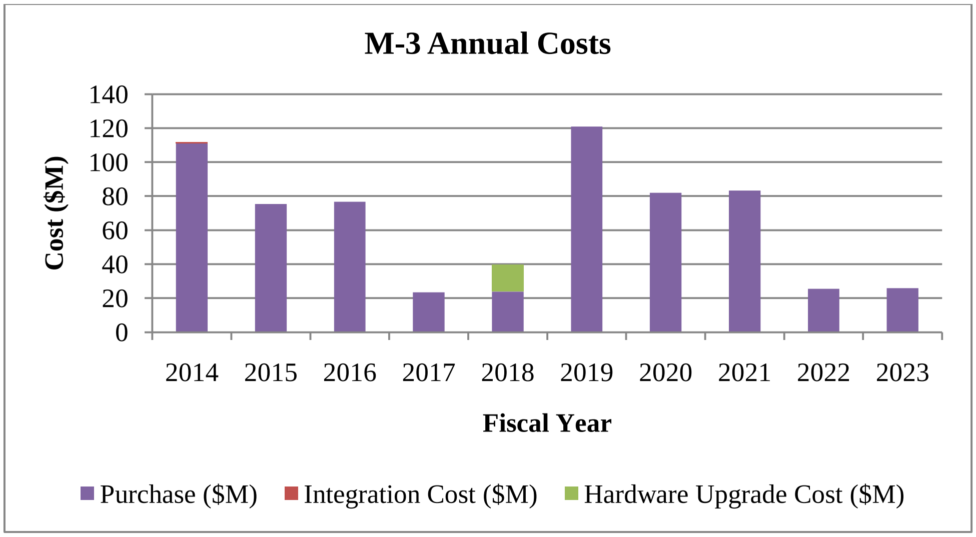


Figure 100 - M-3 Annual Costs

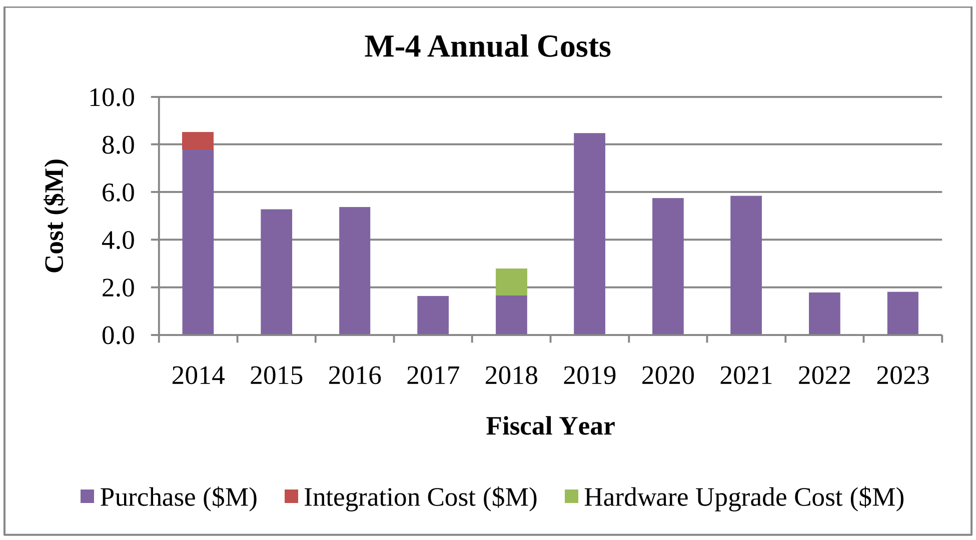


Figure 101 - M-4 Annual Costs

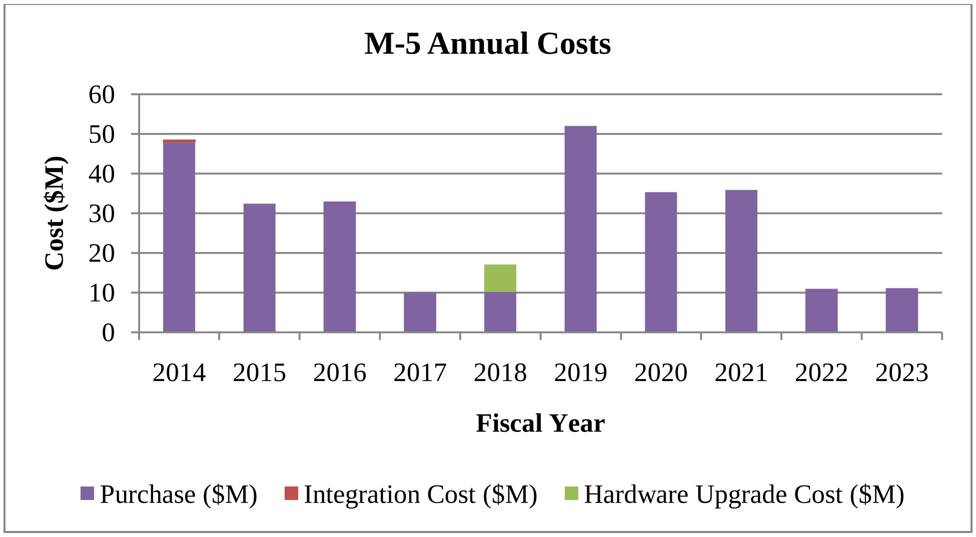


Figure 102 - M-5 Annual Costs

(2) NPV Comparison by Weapon. The annual costs were first calculated for each of the RUINS munitions. Then for each of the RUINS munitions, the average of the annual costs over a 10-year span, 2014–2023, was calculated to determine the Net Present Value (NPV). The NPV Cost comparison by weapon can be seen in Figure 103. The results show that the RUINS GB-2, which was modeled after Textron Defense Systems' Selectively Targeted Skeet weapon, had the highest NPV at almost $1.2 billion. The RUINS Bomb, which was modeled based on a theoretical 10-lb gravity bomb, had the lowest NPV at $800 thousand. This depicts how much it would cost today to undertake one of these munitions projects.

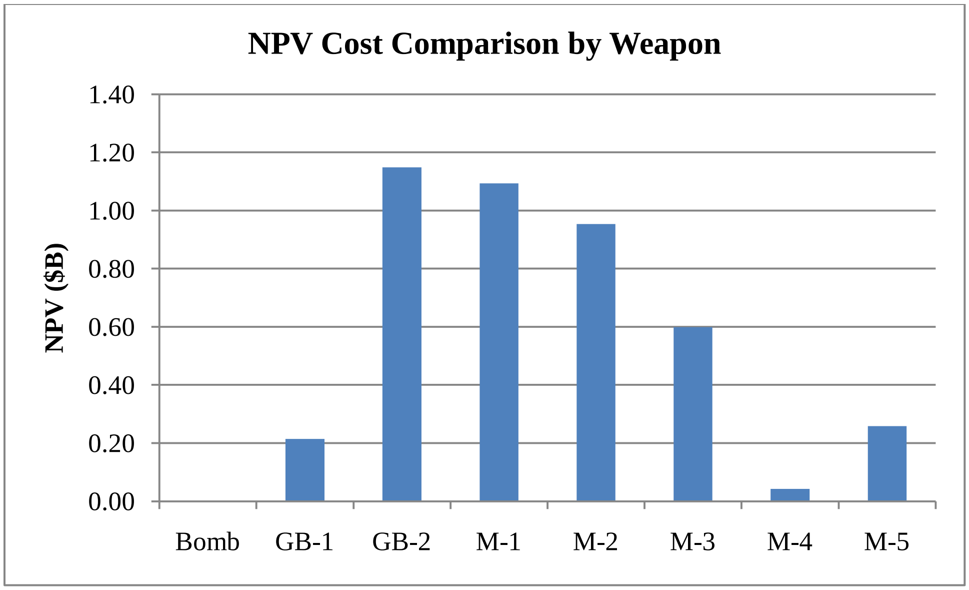


Figure 103 - NPV Cost Comparison by Weapon

7. Cost Benefit Analysis

The modeling and simulation results for each KPP in correlation with each weapon were then entered into its respective KPP scoring equation as seen in Chapter 2, section E. For example, the weapon accuracy M&S results for the M-4 was entered into the scored weapon accuracy scoring equation, which was *Scored Miss Distance = (Miss Distance – KPP Goal) / (KPP Threshold – KPP Goal).* This number was then multiplied by the KPP weighted value, as seen in Figure 17, which for weapon accuracy was 0.123. This is completed for all the KPPs and results grouped into categories "UAV Performance & Susceptibility," "Weapon Delivery," and "Weapon Warhead Effectiveness." The individual KPP scores were totaled for each category and given a total score for that category. For instance the KPP score for "Weapon Effectiveness" for the M-4 weapon was created by adding together the "Weapon 50% P_K Value Range Human (Radius)" and "Weapon 50% P_K Value Range Truck (Radius)," giving the M-4 a total weapon effectiveness score of 0.11. The last step was adding all categories together for a given weapon resulting in a total OMOE as seen in Table 56.

Table 56 - OMOE Weights

Weapon	UAV Performance & Susceptibility	Weapon Delivery	Weapon Warhead Effectiveness	Total OMOE
Bomb	0.095	0.013	0	0.108
GB-1	0.126	0.145	0	0.271
GB-2	0.095	0.156	0.192	0.443
M-1	0.074	0.088	0	0.162
M-2	0.135	0.215	0	0.350
M-3	0.143	0.164	0	0.307
M-4	0.213	0.269	0.820	0.564
M-5	0.247	0.183	0.192	0.622

These OMOE scores were then entered into a cost as an independent variable (CAIV) calculation.

> *CAIV is a strategy for acquiring and supporting defense systems that entails setting aggressive, realistic cost objectives (and thresholds) for both new acquisitions and fielded systems, and managing to those objectives. The cost objectives must balance mission needs with projected out-year resources, taking into account anticipated process improvements in both DoD and defense industries (Beach n.d.).*

A CAIV takes the weapon OMOEs and graphs it against NPV weapon cost. The CAIV data results are in Table 57.

Table 57 - CAIV Data

Alternative	NPV ($M FY11)	OMOE
Bomb	$0.8	0.108
GB-1	$213.9	0.271
GB-2	$1,148.8	0.443
M-1	$1,093.3	0.162
M-2	$953.5	0.350
M-3	$598.7	0.307
M-4	$42.6	0.567
M-5	$257.9	0.622

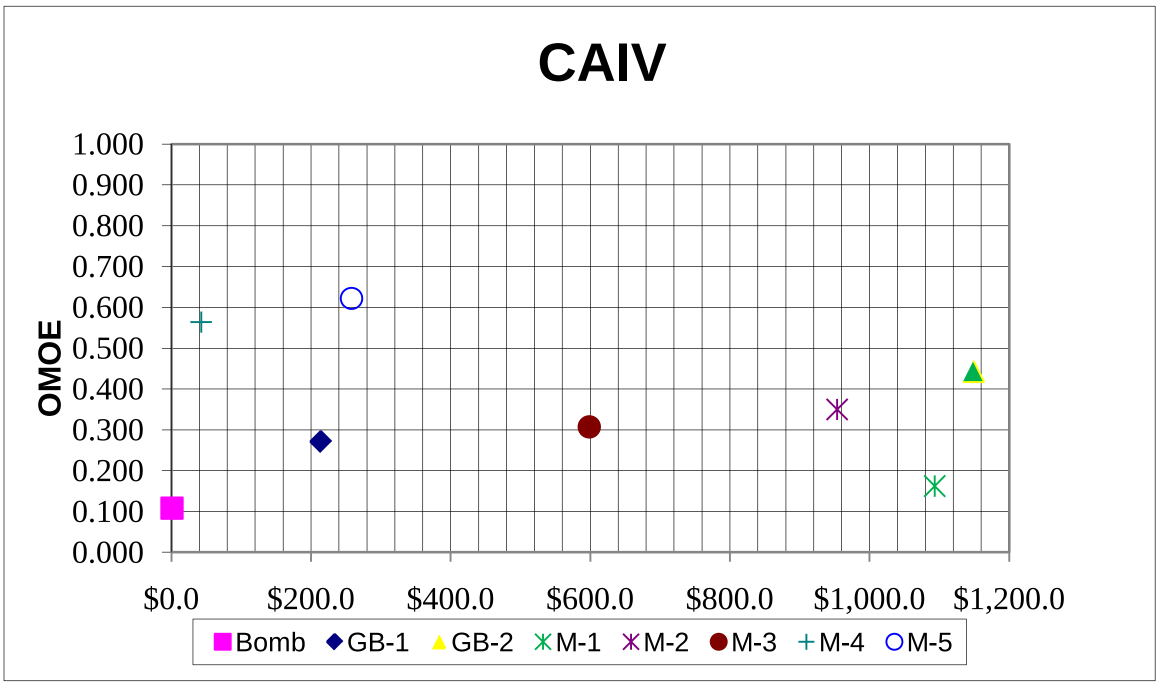


Figure 104 - CAIV

8. Cost Recommendations

Based on the CAIV results, the M-4, M-5 and bomb are the non-dominated solutions on the Pareto boundary. M-5 is one optimal solution having highest OMOE at 0.622 and a NPV of $257.9 million. However, the M-4 is also an optimal solution having the second highest OMOE at 0.564, while having the second lowest NPV cost at $42.6

million dollars. The bomb, while a possible solution, is interesting because it had the lowest NPV at $800,000 but it had the lowest OMOE at 0.161 which is too low to be a practical solution. Although upgrades can be done to the bomb to raise the OMOE to an acceptable score while still keeping the total NPV below all the weapon options, it does not seem feasible at this time. Even though the basic bomb can be upgraded, there may not be enough time to visit these options. The weaponized UAV is needed currently by the coalition forces. In conclusion, reviewing the collected data, M-4 is the weapon of choice, if the UAV is to be armed. The tradeoff made for M-4 over M-5 was less effectiveness for greater cost savings.

G. Synthesis of Optimum Solution

Four different modeling and analysis procedures were used to ascertain the strengths and weaknesses of the candidate Tier II weapon solutions. Each procedure focused on a separate portion of the proposed weapons, utilizing open source information developed during the Problem Identification phase and the Design and Analysis phase. "Performance Modeling and Simulation" used notional weapon models created using the most accurate, available open source specifications. This data was used in the Joint Integration Mission Model environment to determine approximate weapon engagement performance in two different scenarios. "Modeling Warhead Effects," including possible collateral damage, was accomplished using engineering assumptions, algebraic methods, and statistical analysis. "Aerodynamic Performance Analysis" assessed decreases to the Tier II UAV aerodynamic performance as a result of the addition of weapons, using the Shadow 600 as a representative model. The evaluation developed notional percentage degradations that were applied to the performance of the surrogate Tier II UAV. Finally, "Cost Analysis" provided financial estimations of the cost effectiveness of each solution, and included a CAIV analysis.

While each of the different modeling and analysis sections provided recommended solutions, the optimum solution must not be selected without consideration of all possible inputs. Therefore, an examination of each analysis and interaction allowed the selection of the optimum solution using the entire modeling and analysis effort. The OMOE was

developed in three sections: weapon engagement performance, warhead performance, and UAV impacts. The OMOE sections were used in discussion of the results for each section.

Performance Modeling and Simulation had several KPPs associated with it: "Minimum Weapon Range," "Maximum Effective Weapon Range," "Weapon Speed," and "Weapon Accuracy." Table 58 shows the candidate weapons' performance in each of these categories, ranked by best performance.

The M-4 system easily offers the best standoff range capability. Its ability to successfully engage a target at a range of over 3 km is impressive and is nearly twice that of its nearest contender, the M-5. While the M-4 miss distance performance was exceeded slightly by both the GB-1 and GB-2, the standoff range of the M-4 is over four times that of the GB-2.

Table 58 - Weapon Performance KPP Rankings

Rank	Maximum Weapon Range (feet)	Weapon Miss Distance (feet)
1	M-4 (11,727)	GB-2 (0.4)
2	M-5 (6,623)	GB-1 (0.4)
3	M-3 (5,043)	M-4 (0.5)
4	M-2 (3,220)	M-2 (8.7)
5	M-1 (3,038)	M-3 (18.2)
6	GB-2 (2,765)	M-5 (91.0)
7	GB-1 (2,339)	M-1 (118.0)
8	Bomb (1,762)	Bomb (651.6)

Warhead performance had two KPPs associated with it. These were applied in the OMOE formula in an effort to reward effective target performance while minimizing collateral damage. Collateral damage was not directly selected as a KPP; however, analysis was provided to allow full understanding of the possible warhead impacts in various operational scenarios. The ranked KPP results of the warhead analysis follow.

Table 59 - Warhead Lethality Radius Rankings

Rank	Lethality Radius of Warhead against Human Target (meters)	Lethality Radius of Warhead against Vehicle Target (meters)
1	GB-2 (0.69)	GB-2 (0.76)
2	M-5 (1.82)	M-5 (2.01)
3	M-4 (3.26)	M-4 (3.59)
4	GB-1 (4.60)	GB-1 (5.08)
5	M-3 (5.92)	M-3 (6.54)
6	Bomb (7.28)	Bomb (8.04)
7	M-2 (9.66)	M-2 (10.66)
8	M-1 (9.90)	M-1 (10.93)

The GB-2 warhead lethality radius performance was exceptional due to the low number of fragments expected in the explosively formed projectile construction. However, the lethality radius is insufficient to successfully address the secondary target of the fixed target scenario even with perfect targeting. The same applies for the M-5 weapon. The lethality radius becomes adequate beginning with the M-4 and GB-1 weapons, requiring precise targeting, which both weapons have demonstrated.

UAV Performance had several KPPs contributing to it, including Maximum Weapons at Takeoff, Maximum Weaponized UAV Range, Maximum Weaponized UAV On-Station Duration, and Stand-Off Range. Aerodynamic Analysis provides the information used to calculate the results for two of these KPPs, as well as an additional derived factor. Though there were some differences in degradation effects for the various options, none are significantly better than others during a full weapon loadout. However, the M-4, GB-1, GB-2, Bomb, and M-5 weapons offer multiple rounds resulting in degradations similar to the effects due to other weapon single rounds. This offers the possibility of operating with less than a full weapon load, reducing the UAV degradation impact if required, as well as possibly increasing actual on-station duration as the UAV would not be required to return to base for rearming after a single target engagement.

Table 60 - Degradation Effects of Weaponization on Tier II UAV Aero Performance (Maximum Weapon Loadout)

Weapon	Weapons on Board	Maximum UAV Range Effect (%)	On-Station Duration Effect (%)	Maximum Speed Effect (%)
M-3	1	-9.2	-19.5	-3.1
M-4	4	-9.5	-20.9	-4.2
M-2	1	-10.0	-21.6	-4.1
GB-1	3	-10.7	-23.2	-4.7
M-1	1	-11.6	-24.9	-5.2
GB-2	2	-12.2	-25.8	-7.0
Bomb	2	-12.2	-25.8	-7.0
M-5	10	-15.1	-29.6	-8.7

The OMOE scores and resulting CAIV recommendations provided interesting data. The CAIV recommendations include the M-4 as the preferred solution, with M-5 and GB-1 preferred second choices. The OMOE scores resulting for the analysis and other measured parameters are presented in Table 61.

Table 61 - Candidate OMOE Rankings

Rank	Candidate	OMOE
1	M-5	0.622
2	M-4	0.564
3	GB-2	0.443
4	M-2	0.350
5	M-3	0.307
6	GB-1	0.271
7	M-1	0.162
8	Bomb	0.108

However, such recommendations cannot be used without full evaluation of all available data. The top-rated weapon from the CAIV analysis, the M-5, though possessing the desirable attributes of large standoff range and multiple weapon capability, displayed an average 91-meter miss distance. Though the miss distances achieved during modeling may be inaccurate, the M-5 includes an underpowered warhead unable to

accomplish the fixed target scenario even with perfect targeting. It is the judgment of the Team that the M-5 should not be considered a possible solution for the presented problem at this time.

Given the analysis performed, the Team recommends the M-4 weapon for use with the Tier II UAV for the accomplishment of the proposed scenarios. Its unsurpassed standoff range, high accuracy, and adequate warhead will allow successful rapid engagement of targets while limiting enemy damage to the UAV and collateral damage. A secondary selection, the GB-2, also offers excellent accuracy and comparable warhead performance but with significantly less standoff range. Both weapons may be used day or night, offering wide operational flexibility. Both also offer the capability of more than one round being on-board the UAV at takeoff, promising longer duration missions and better protections for the Warfighter.

THIS PAGE INTENTIONALLY LEFT BLANK

V. CONCLUSIONS AND RECOMMENDATIONS

The purpose of the investigation was to determine the feasibility of arming Tier I and Tier II UAVs in aiding the C-IED mission. System engineering processes were used throughout the project in analysis of requirements and stakeholder needs, functional analysis, and the generation of an objectives hierarchy. SE tools were used to help map the needs to hardware, resulting in a notional architecture. Research was performed using open sources for identification of possible solutions and gathering the information necessary for the analysis of alternatives and development of models. Modeling of candidate solutions and their financial and operational implications led to identification of the optimum solution for each Tier of UAV.

A. Conclusions

Tier I UAVs are not feasible for weaponization in their current configuration. The analysis in Chapter 3 indicates that due to the very small available payload capacity, the only feasible weapon would be an explosive nose cone. However, this implementation could prove potentially dangerous for personnel. If the nosecone is armed with some explosive device, safety would dictate having a mechanical safe-arm device to allow safe transport. While in safe mode, even if the primer were to go off, the full warhead would not detonate. However, in preparation for launch, the safe-arm would be set to "armed." As this Tier of UAV is hand-launched, there is the distinct possibility it could hit the ground close to the launching personnel and trigger detonation.

Based on cost analysis and weapons effectiveness modeling, the RUINS Team found the optimum solution for the Tier II UAV is either the M-4 or the GB-1 weapons. Either selection offers the possibility of multiple weapons being onboard the aircraft at takeoff, allowing for the attack of more than one target and longer on-station persistence. Both offer engagement ranges outside of the anticipated enemy defense range, though within visual detection range. With low cost and high performance, the M-4 is suitable for the needs of the C-IED mission. A second recommended alternative is the GB-1. The cost effectiveness may outweigh the poor performance shown in the modeling and simulation depending on the needs of the user.

B. Logistics Conclusions

As previously stated, the logistics and support will be largely similar to existing UAS and weapon support. The UAS unit currently includes several UAVs, ground control stations, launcher, recovery device, personnel, transport vehicles, repair equipment, and enough spares and supplies to operate for a specified amount of time. This would be expanded to include the M-4 weapon and its associated storage, repair, and transportation equipment.

Due to the cost, complexity, and small size of the weapon, only depot-level maintenance should be required. In the field, a built-in self-test would be performed. If the weapon failed the test, it would be removed and shipped back for repairs. Assuming adequate stores, maintaining weapons in the field is unnecessary. Depending on the operations tempo, and the number of weapons fired per mission, a significant number of weapons could be required. For example if all four missiles were fired every mission, and two missions were carried out in a 24 hour period, then 56 M-4 missiles would be needed to sustain a week's worth of operations.

1. Operational Support

Operations would be supported through the normal methods for UAS units with the addition of some specialized personnel. Personnel would need to be trained to properly handle, load, and unload weapons from the UAV. The pilot would need to be trained on the capabilities, tactics, and operation of the weapon. EOD personnel would have to be collocated or be nearby to handle hang fires or jettisoned weapons.

After integrating the new equipment and armament, the users must be trained. It is essential that the users are well equipped with the knowledge to operate the equipment as people's lives hang in the balance. New displays, controls, and procedures associated with the M-4 will require the operator to complete additional training. Employing the weapon correctly will come from a combination of operational, computer-based, and classroom training. Training is just as important as the operational availability of the weapon. If the weapon is functional and the user cannot operate it, the mission is a failure.

2. Disposal and Demilitarization

Disposal would again be similar to current operations. The current components of the UAS would be no different than the systems currently fielded. Weapons would be kept separate and disposed of as they typically are in accordance with regulations.

C. Solution Risks

Final selection of M-4 as the optimal solution allowed closer examination of the risks involved with continuing to pursue its integration with the Tier II UAV. These risks have the potential to severely impact the successful development of the RUINS. Identification of the anticipated risks, their likelihood of occurrence, and possible consequences will allow active monitoring and management as the project proceeds to its future phases.

A primary risk is the selected alternative. The risk is due to the lineage of much of the data used in performing analysis and tradeoffs. Identification of M-4 as the optimum alternative relied heavily on modeling and simulation during the selection of alternatives. While efforts were made to obtain accurate and representative data, many of the systems investigated during the project were notional and prototypes, including the M-4. In the absence of documented open-source data, engineering estimates or approximations were used. These estimates may have caused an unintended biasing in the selection process. The consequences resulting from this risk are severe if not monitored closely. Large amounts of effort and funding could be expended pursuing a solution that is not truly feasible. To mitigate the risk, the Team recommends further modeling and analysis when more data becomes available, or modeling in a classified environment, before proceeding further with any acquisition plans.

A second risk is associated with the integration of the selected weapon system with the UAS. It was assumed early in the project that the UAV airframe would be able to endure the additional stresses caused by the mounting, transport, and operation of the weapon system. It was also assumed that the UAV would be able to power the weapon system and any necessary support equipment without modification. Finally, the onboard and ground control processing resources were assumed to be capable of hosting and performing any additional software instructions necessary for the successful control of the

weapon system. These assumptions form a significant risk judged to have a medium likelihood of occurrence but with severe consequences. If such an event occurs, severe implementation delays and financial impacts could result. To mitigate this risk, the Team recommends immediate stress and aero analysis, and better determination of power and processing requirements to better gauge required resources against those currently available.

A final identified risk is with the specific identified option. The M-4 system includes rocket propulsion. There is some concern that the rocket motor may crack during repeated takeoffs and landings. Damage to the motor could cause failure of the motor, increased maintenance requirements, and unreliable operation. The likelihood of occurrence was judged to be low as other rocket motors have experienced similar loads without failure, with a relatively severe consequence if it occurred, as the selection process would have to be repeated. To mitigate, the Team recommends better definition of the anticipated load environment and continuing efforts throughout the procurement process to insure the motor will perform as intended.

To assist in the tracking of the risks, a graphical depiction of the identified risks, their associated likelihood of occurrence, and relative consequence of occurrence was constructed. This graph is presented as Figure 105.

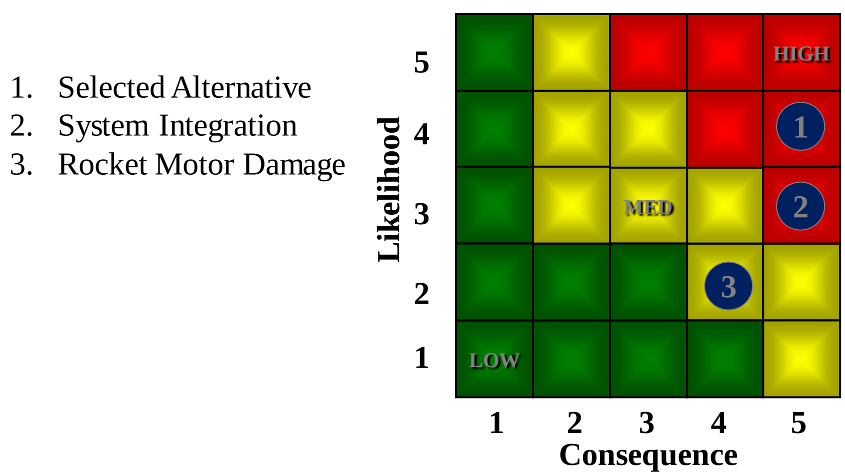


Figure 105 - RUINS Risk Matrix

D. Recommendations

The following list captures the recommendations suggested by the RUINS team.

- The modeling should be run again using more accurate information and more encompassing scenarios. The analysis performed during the project was based entirely on open source information. Open source information can be quite accurate; it can also be entirely incorrect. While there is a significant amount of information relevant to the topic, much of it was not approved for public release. In many cases, engineering estimates were made or time-consuming searches for approximate or equivalent information were conducted. The accuracy of input data certainly affects the accuracy of the modeling outputs.
- Investigate improving the WMS and Ground Control Station hardware and software suite for the Tier II UAV. The WMS concept need not be applied to just weapons, but other items that could support ISR or C-IED missions. This would allow the payload controller to have C2 over anything from a weapon to another sensor package.
- Instead of arming a Tier I UAV, consider AeroVironment's Switchblade. This device is designed to be disposable. To address the safety concerns during launch mentioned earlier, it comes packed in a launch tube and is ejected into flight by a propulsive charge. The operator is able to maintain a safe distance during this operation.
- Research a more appropriate use of the available payload in the Tier I UAV. The Team suggests that instead of arming, the Warfighter would be better served by improving and enhancing the onboard imaging capabilities, allowing it to better perform its existing ISR mission or just extending the endurance.
- Research and investigation into identifying the optimum detector-tracking system is recommended. The lack of detailed system information and the modeling package selected for the project did not offer the specialization required for this important task.

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix A Functional Hierarchy

Perform External RUINS Control

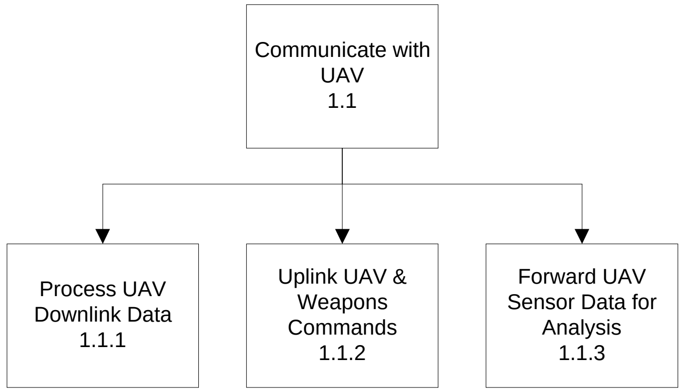


Figure A-1 - Communicate with UAV Functional Hierarchy

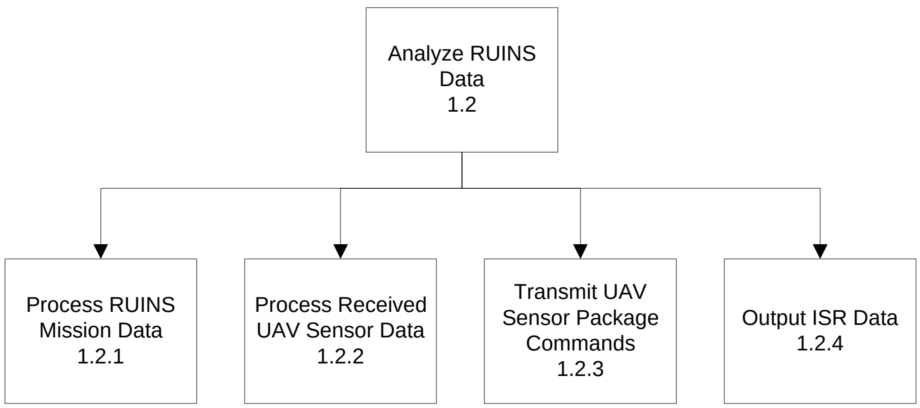


Figure A-2 - Analyze RUINS Data Functional Hierarchy

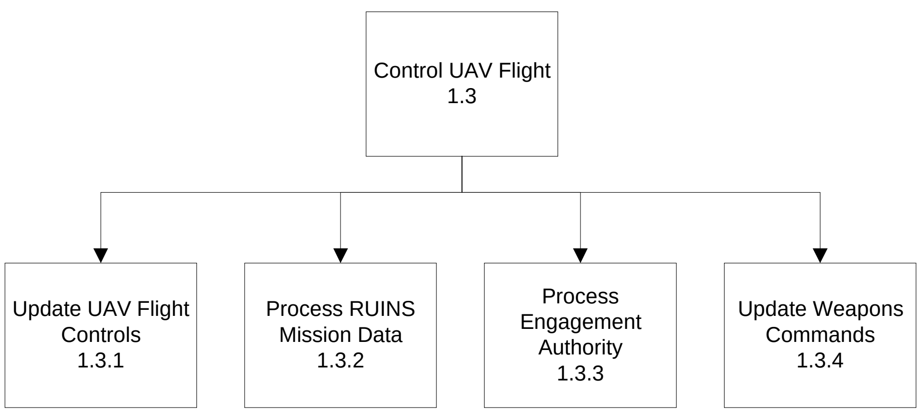


Figure A-3 - Control UAV Flight Functional Hierarchy

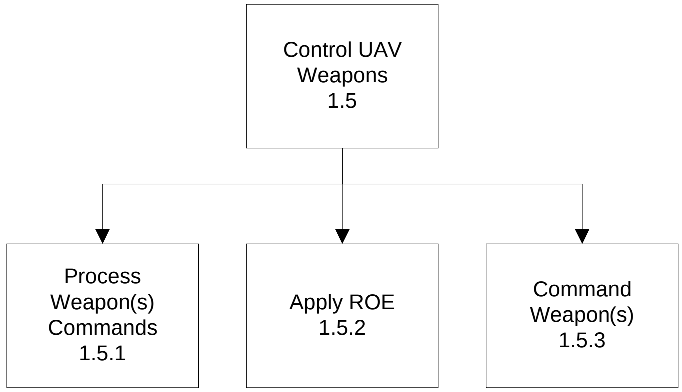


Figure A-4 - Control UAV Weapons Functional Hierarchy

Prepare and Launch RUINS

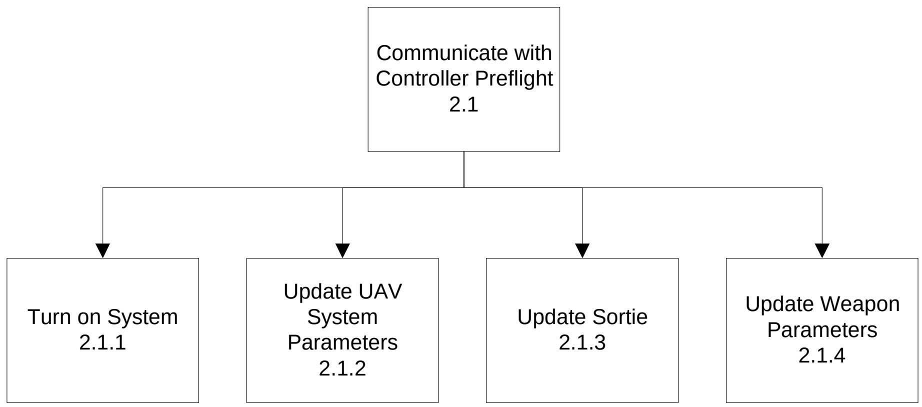


Figure A-5 - Communicate with Controller Preflight Functional Hierarchy

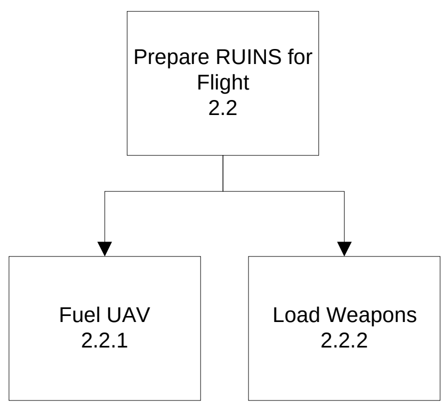


Figure A-6 - Prepare RUINS for Flight Functional Hierarchy

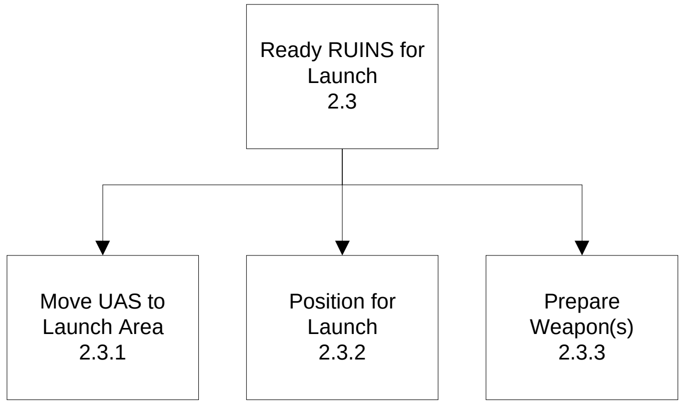


Figure A-7 - Ready RUINS for Launch Functional Hierarchy

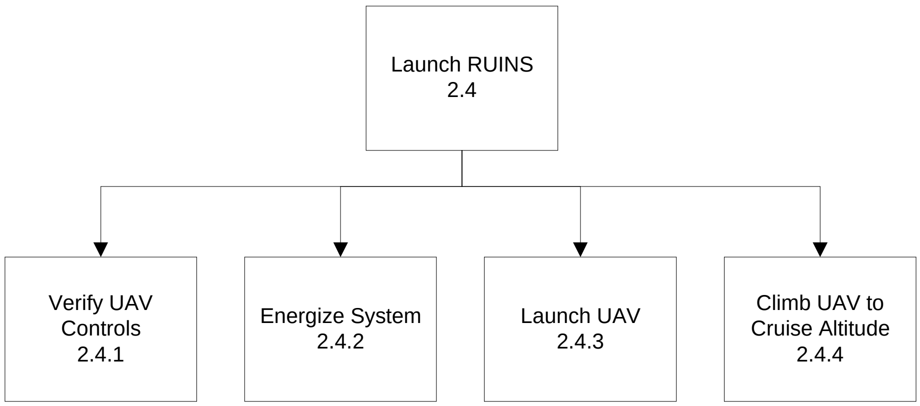


Figure A-8 - Launch RUINS Functional Hierarchy

Fly RUINS Mission

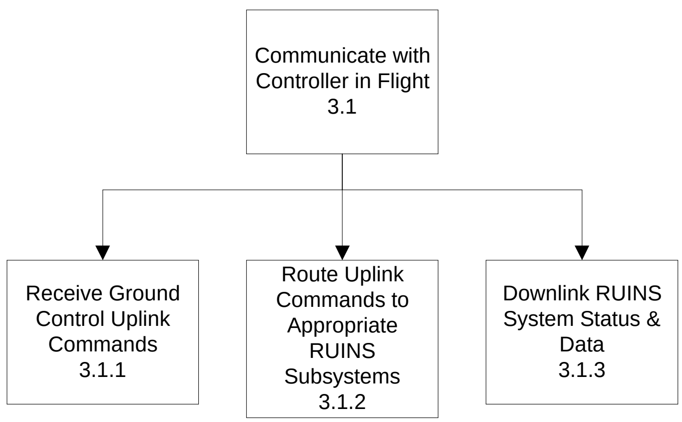


Figure A-9 - Communicate with Controller in Flight Functional Hierarchy

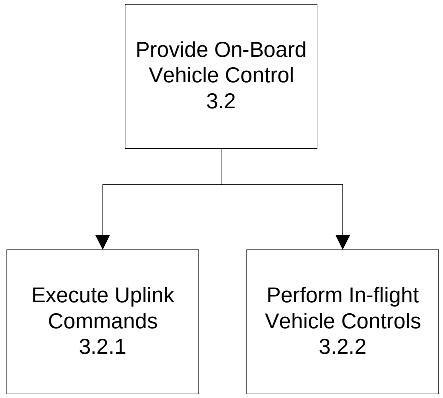


Figure A-10 - Provide On-Board Vehicle Control Functional Hierarchy

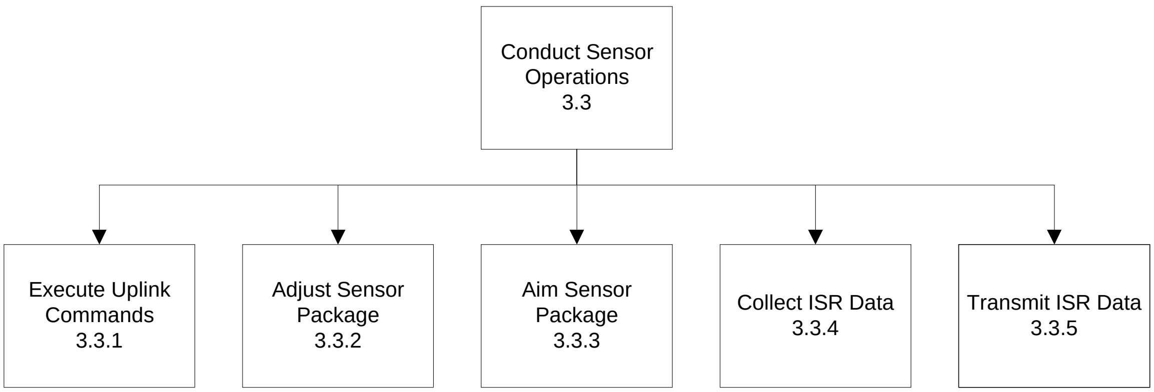


Figure A-11 - Conduct Sensor Operations Functional Hierarchy

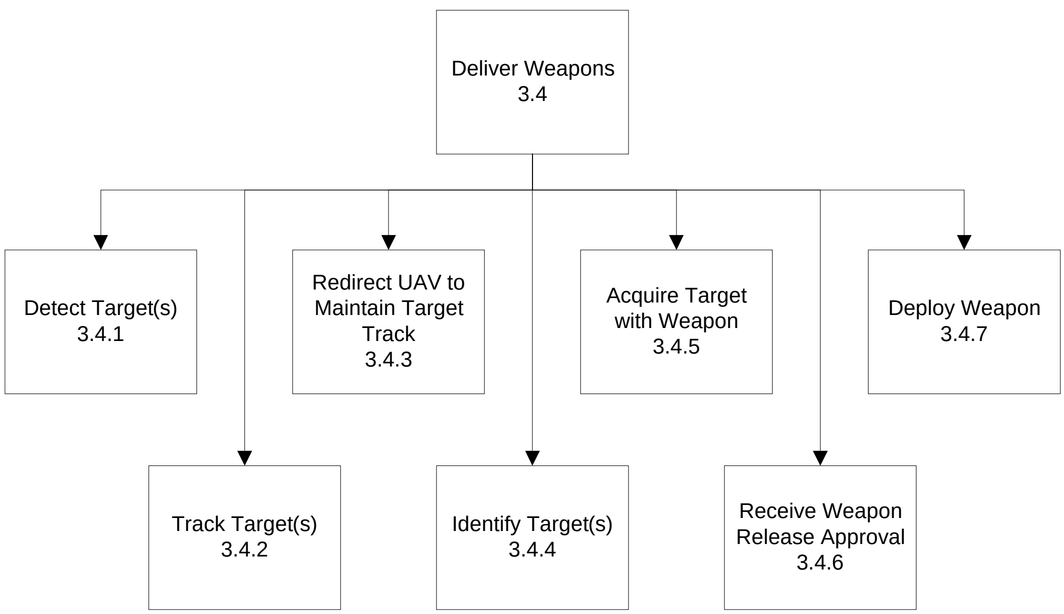


Figure A-12 - Deliver Weapons Functional Hierarchy

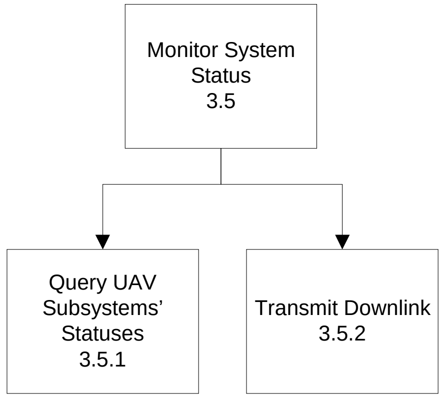


Figure A-13 - Monitor System Status Functional Hierarchy

Recover UAS

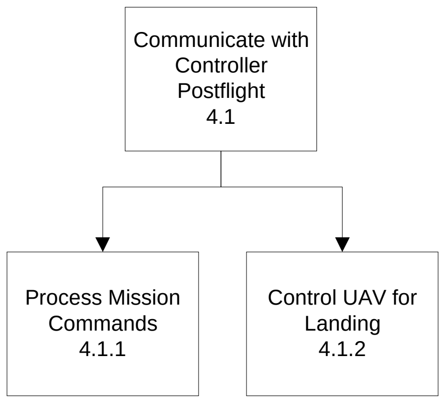


Figure A-14 - Communicate with Controller Post-flight Functional Hierarchy

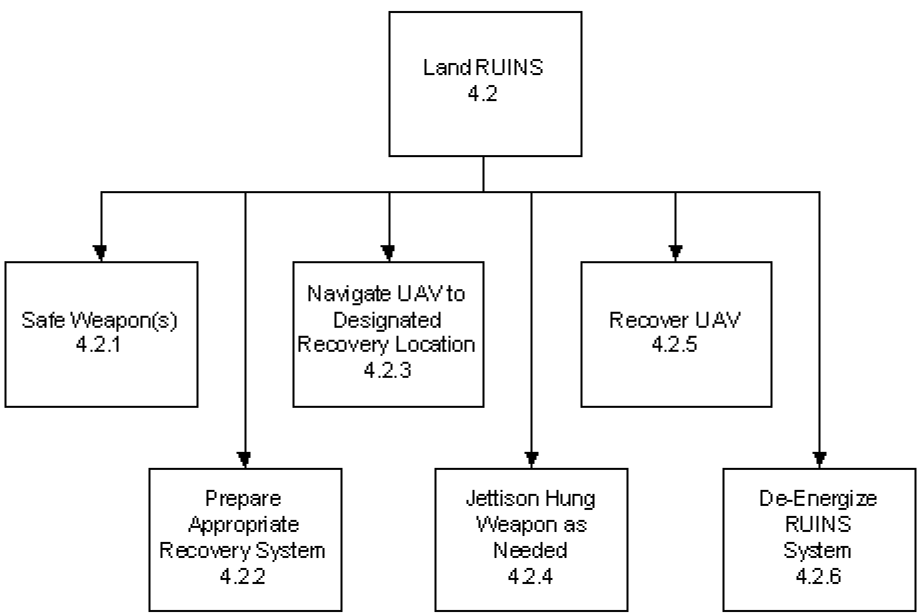


Figure A-15 - Land RUINS Functional Hierarchy

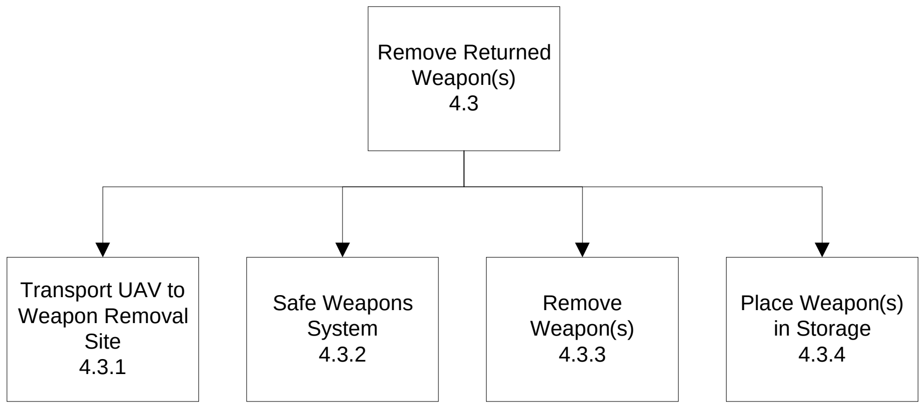


Figure A-16 - Remove Returned Weapon(s) Functional Hierarchy

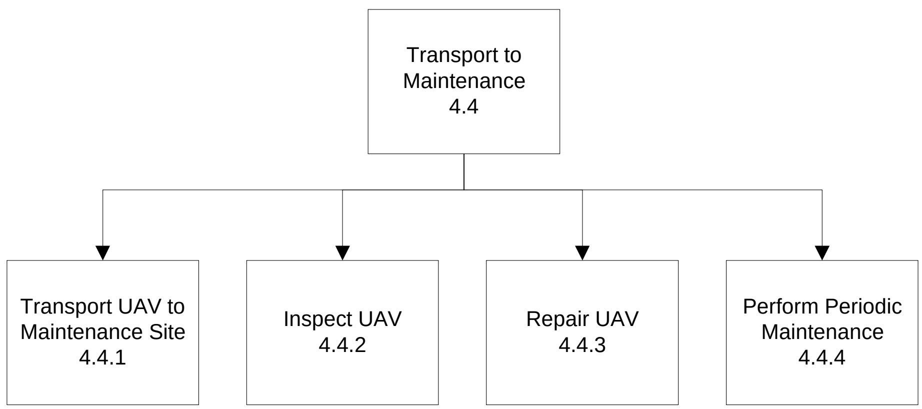


Figure A-17 - Transport to Maintenance Functional Hierarchy

Appendix B Functional Flow Block Diagrams

Perform External RUINS Control

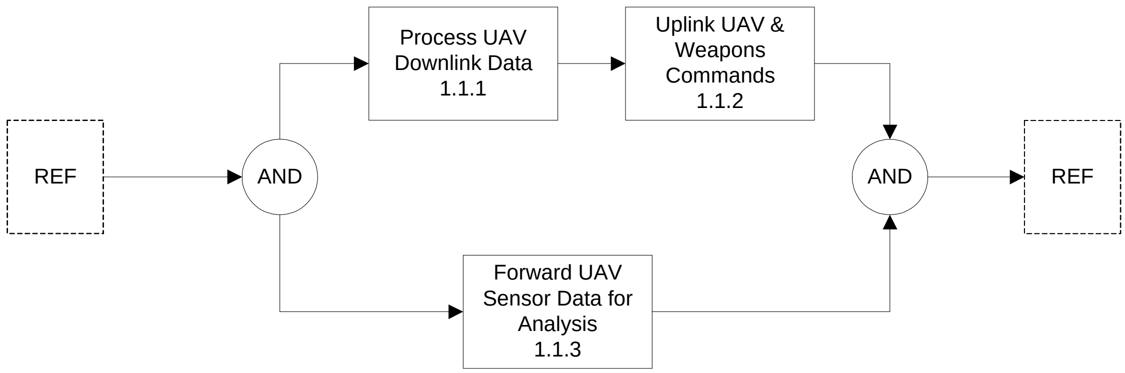


Figure B-1 - Communicate with UAV FFBD

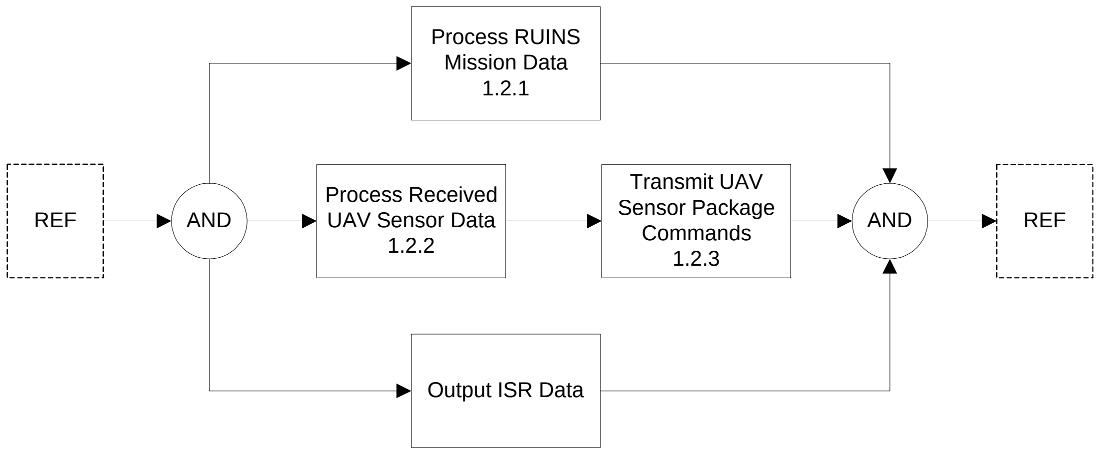


Figure B-2 - Analyze RUINS Data FFBD

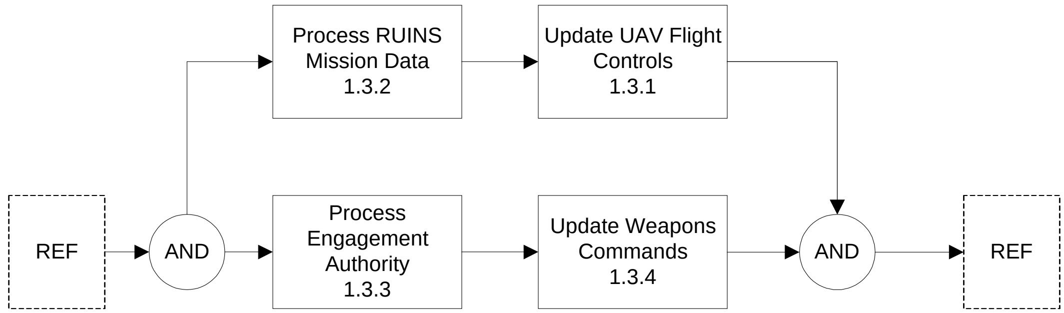


Figure B-3 - Control UAV Flight

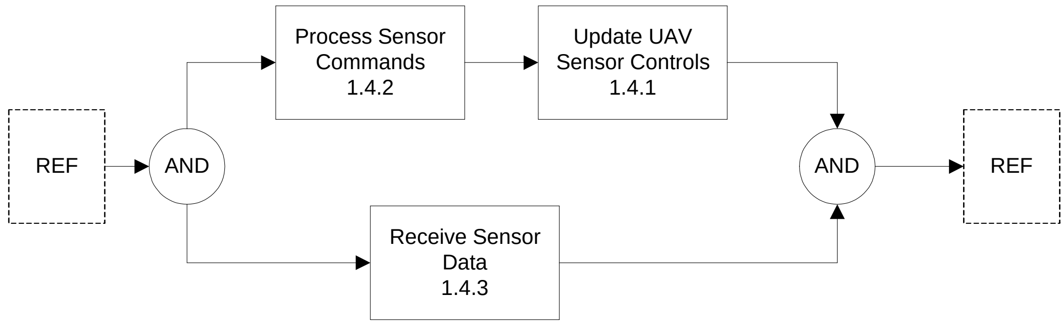


Figure B-4 - Control UAV Sensors

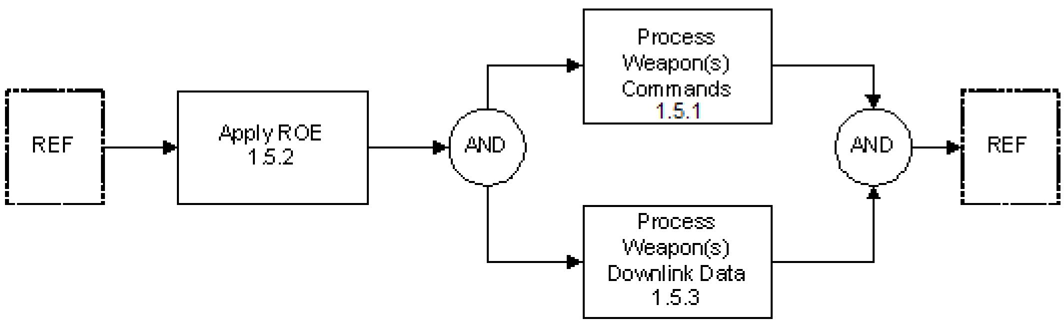


Figure B-5 - Control UAV Sensors

Prepare and Launch RUINS

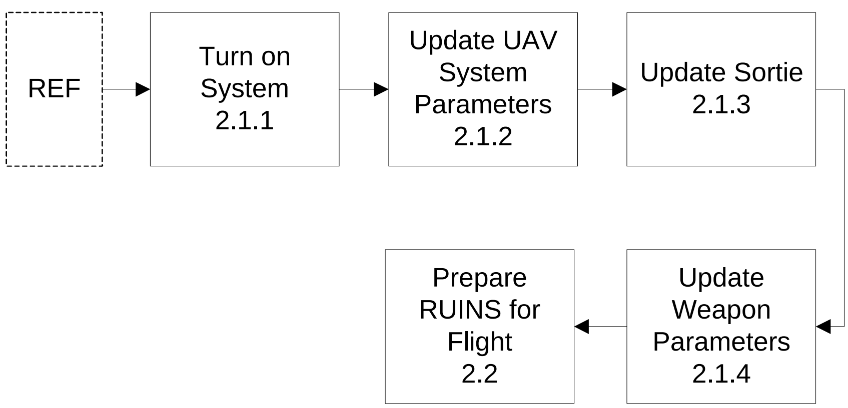


Figure B-6 - Communicate With Controller Preflight FFBD

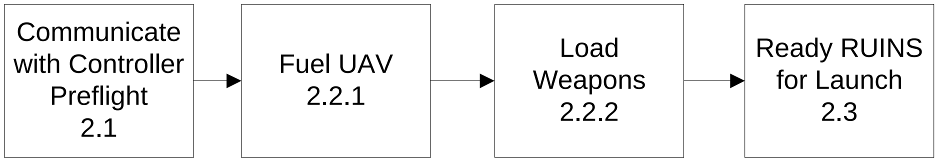


Figure B-7 - Prepare RUINS for Flight FFBD

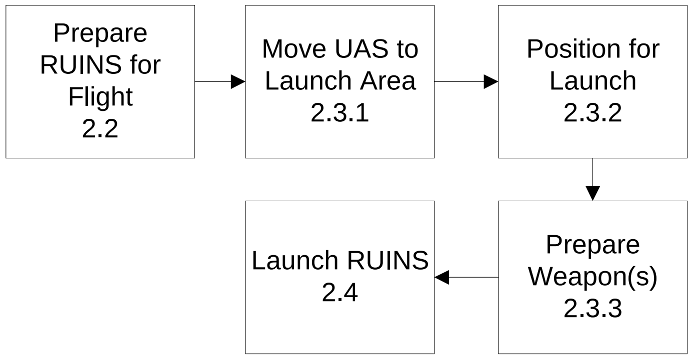


Figure B-8 - Ready RUINS for Launch FFBD

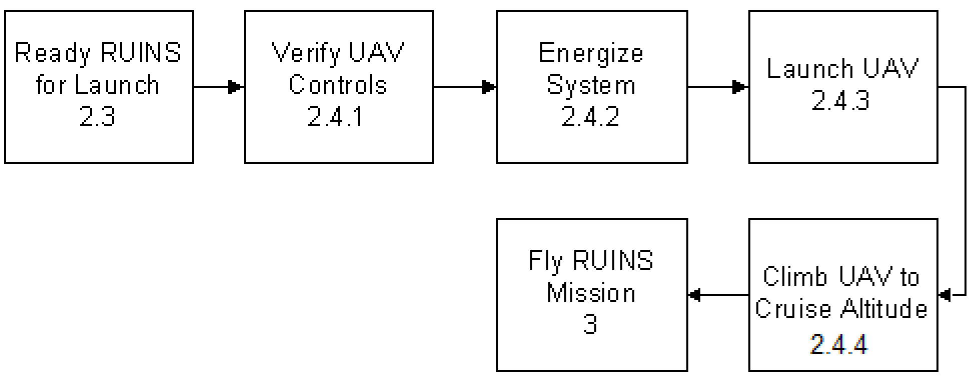


Figure B-9 - Launch RUINS FFBD

Fly RUINS Mission

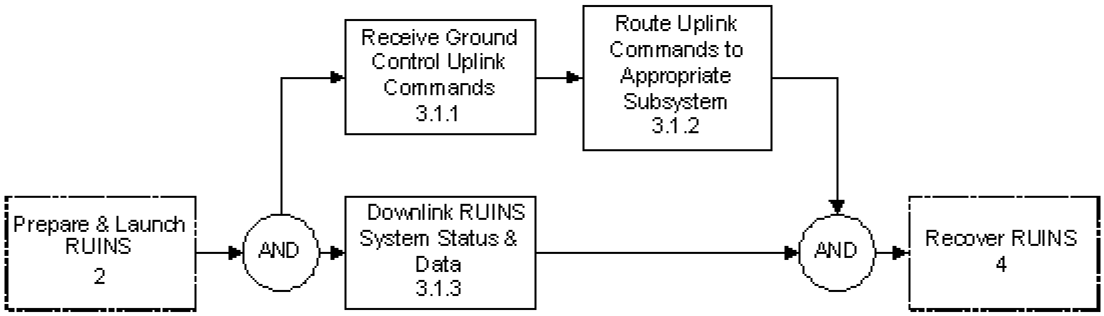


Figure B-10 - Communicate with Controller in Flight FFBD

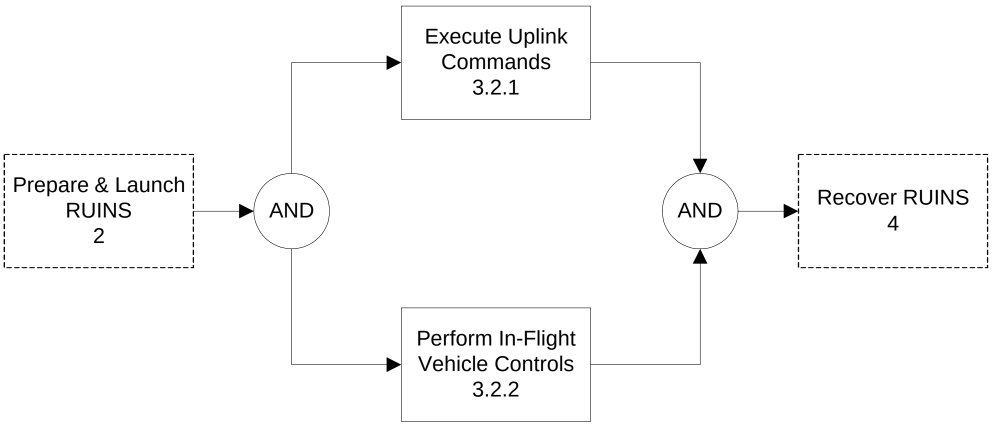


Figure B-11 - Provide On-Board Vehicle Control FFBD

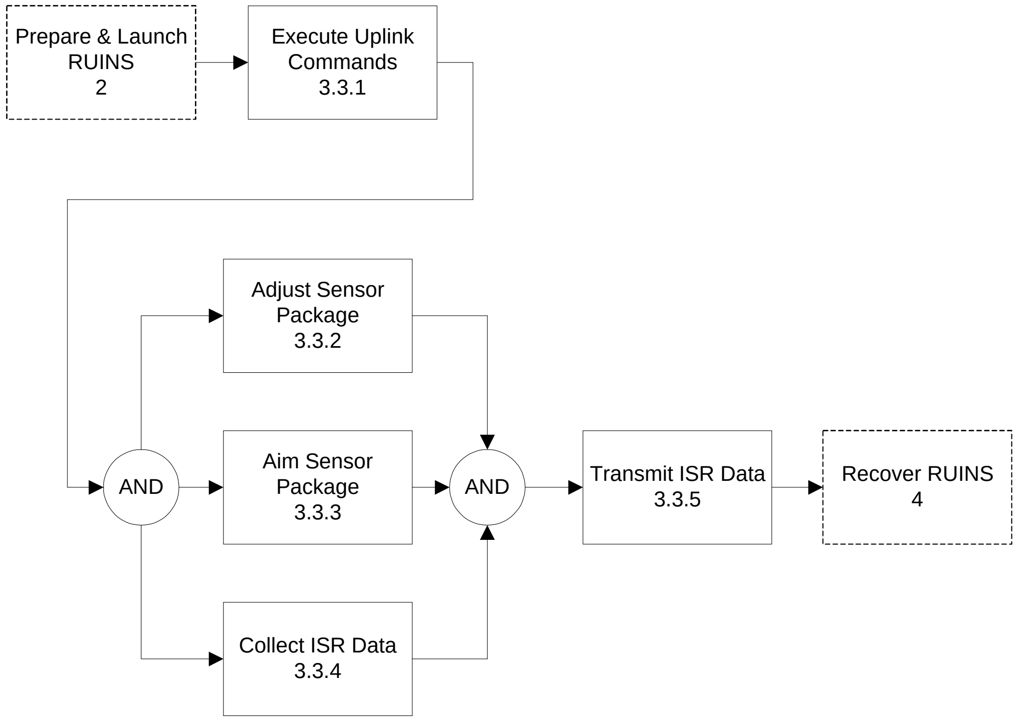


Figure B-12 - Conduct Sensor Operations FFBD

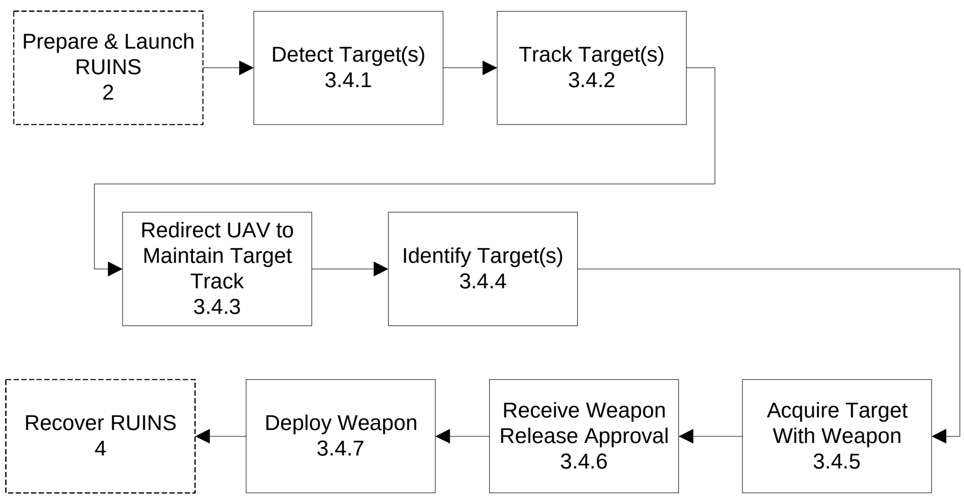


Figure B-13 - Deliver Weapons FFBD

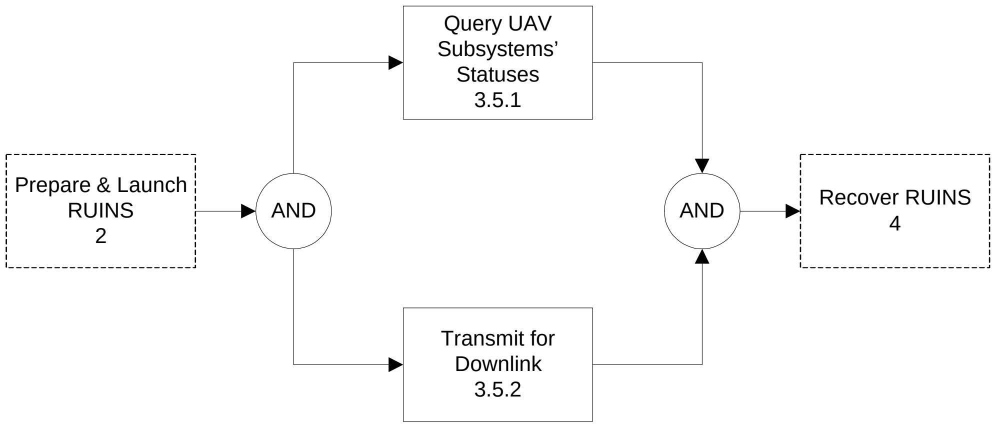


Figure B-14 - Monitor System Status FFBD

Recover RUINS

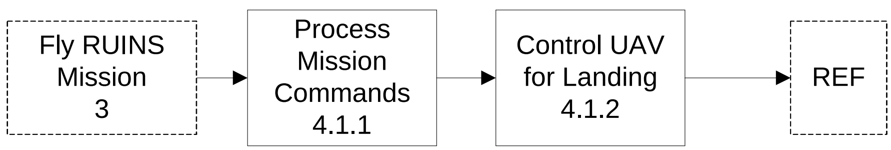


Figure B-15 - Communicate with Controller Post-flight FFBD

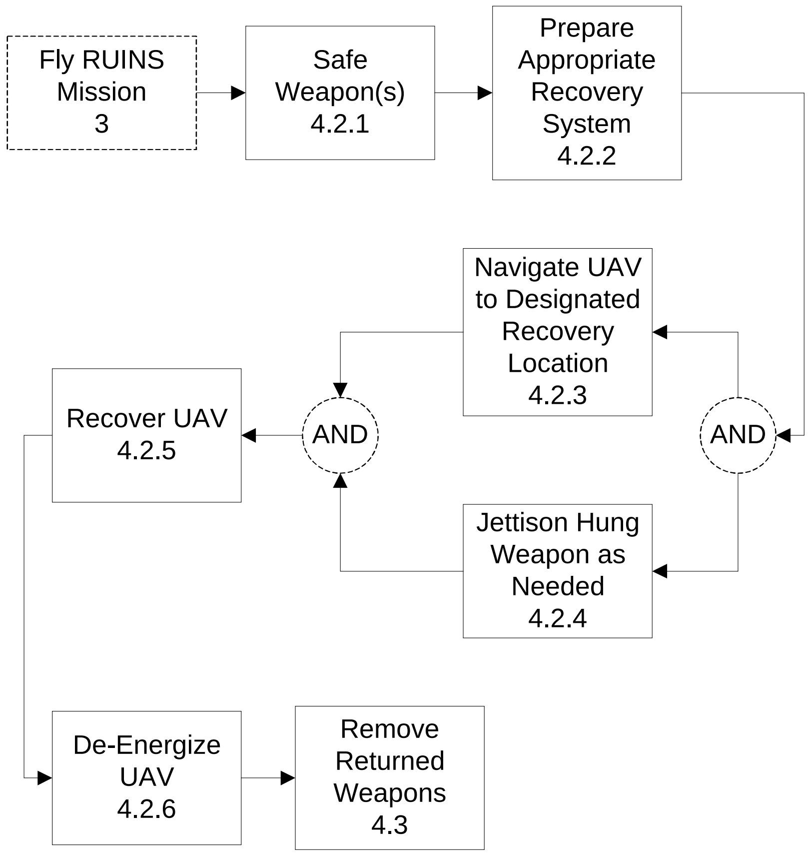


Figure B-16 - Land RUINS FFBD

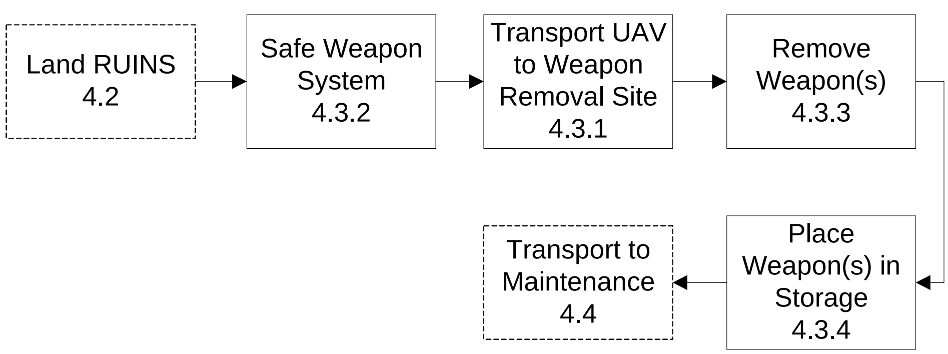


Figure B-17 - Remove Returned Weapon(s) FFBD

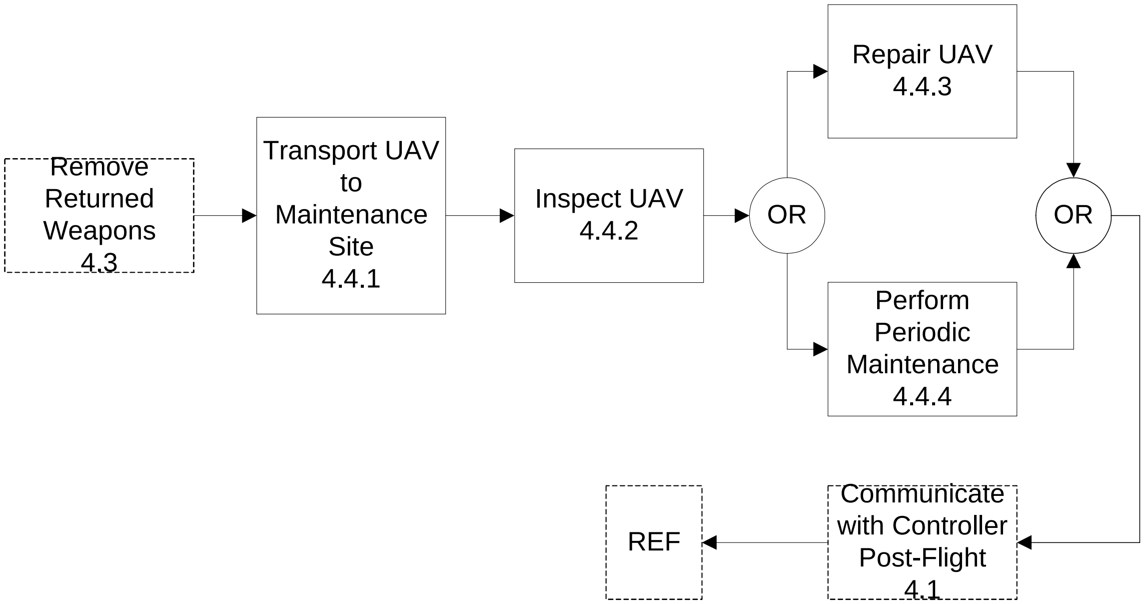


Figure B-18 - Transport UAV to Maintenance FFBD

Appendix C IDEF-0 Breakout

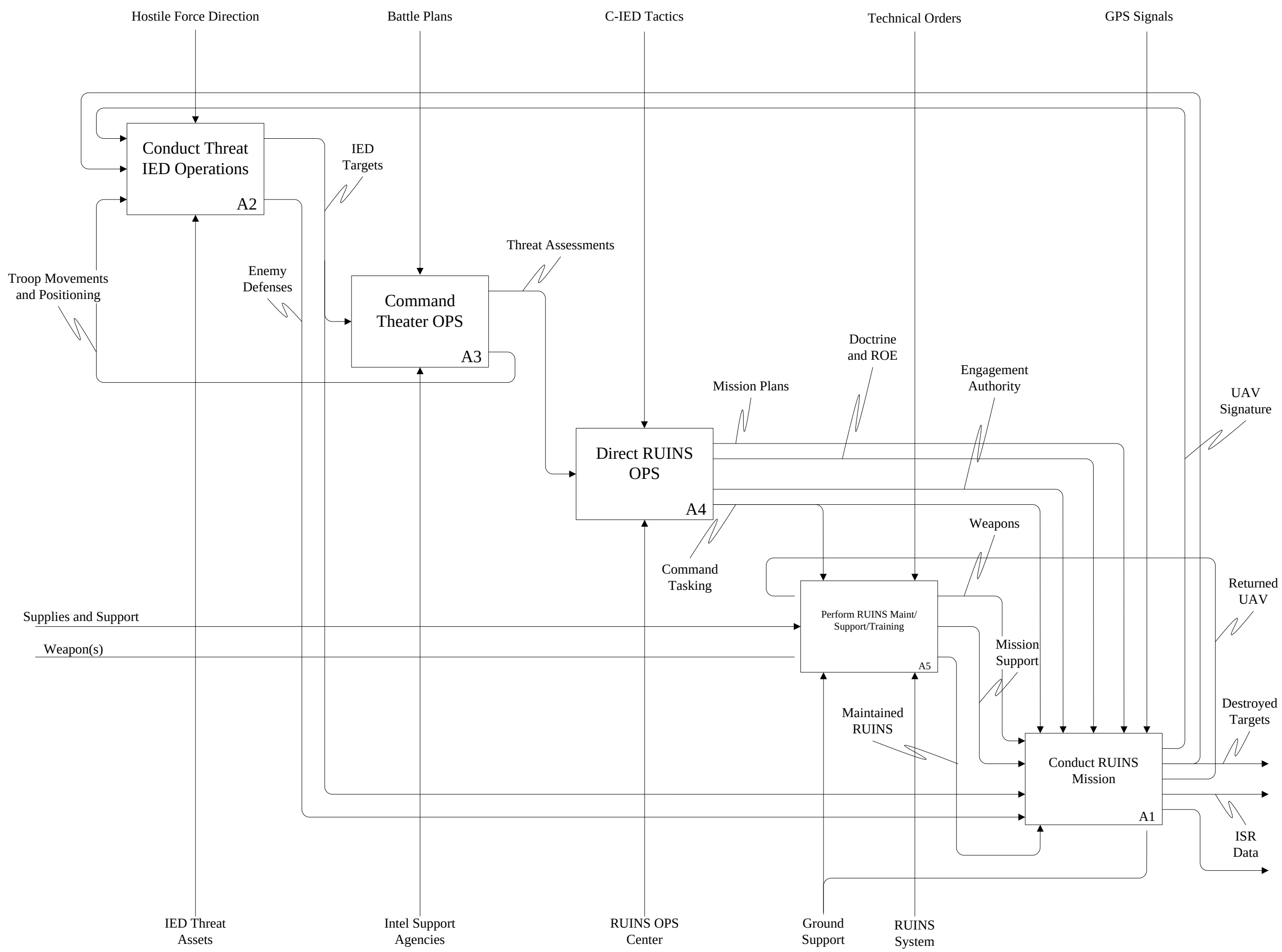


Figure C-1 - RUINS A-1

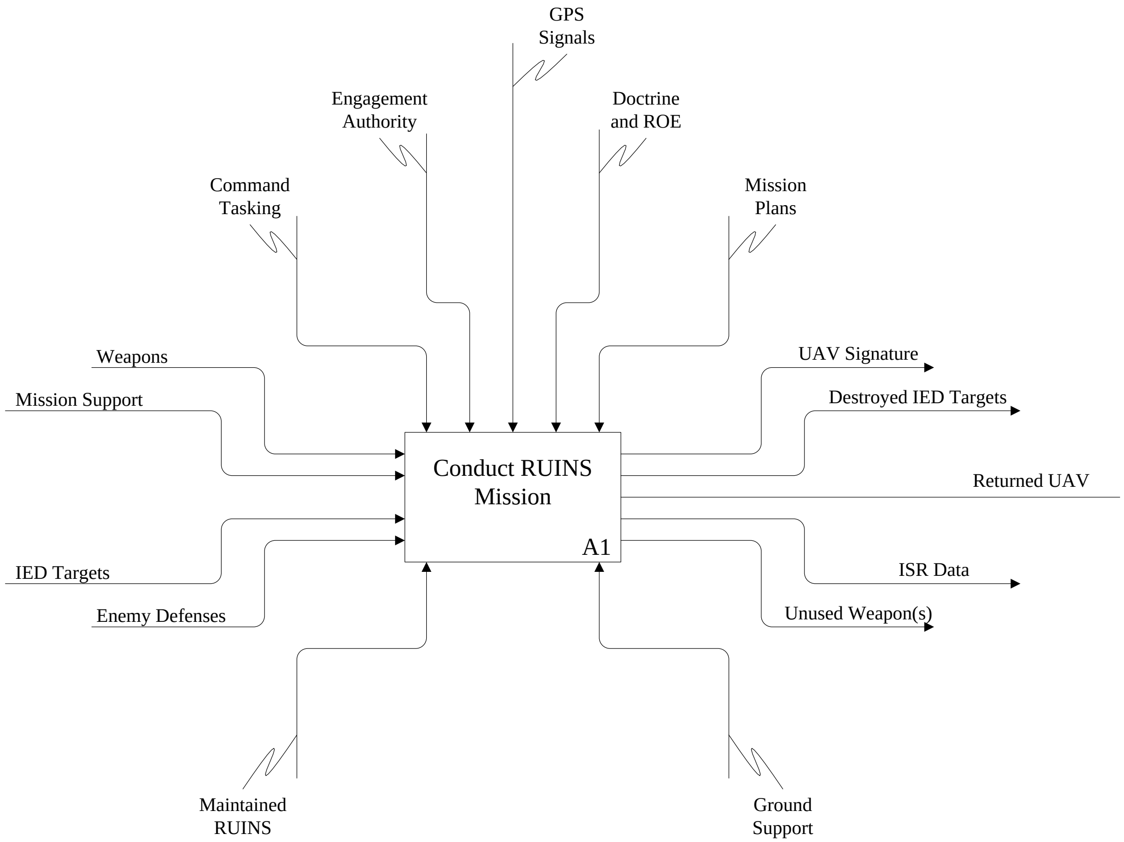


Figure C-2 - RUINS A-0

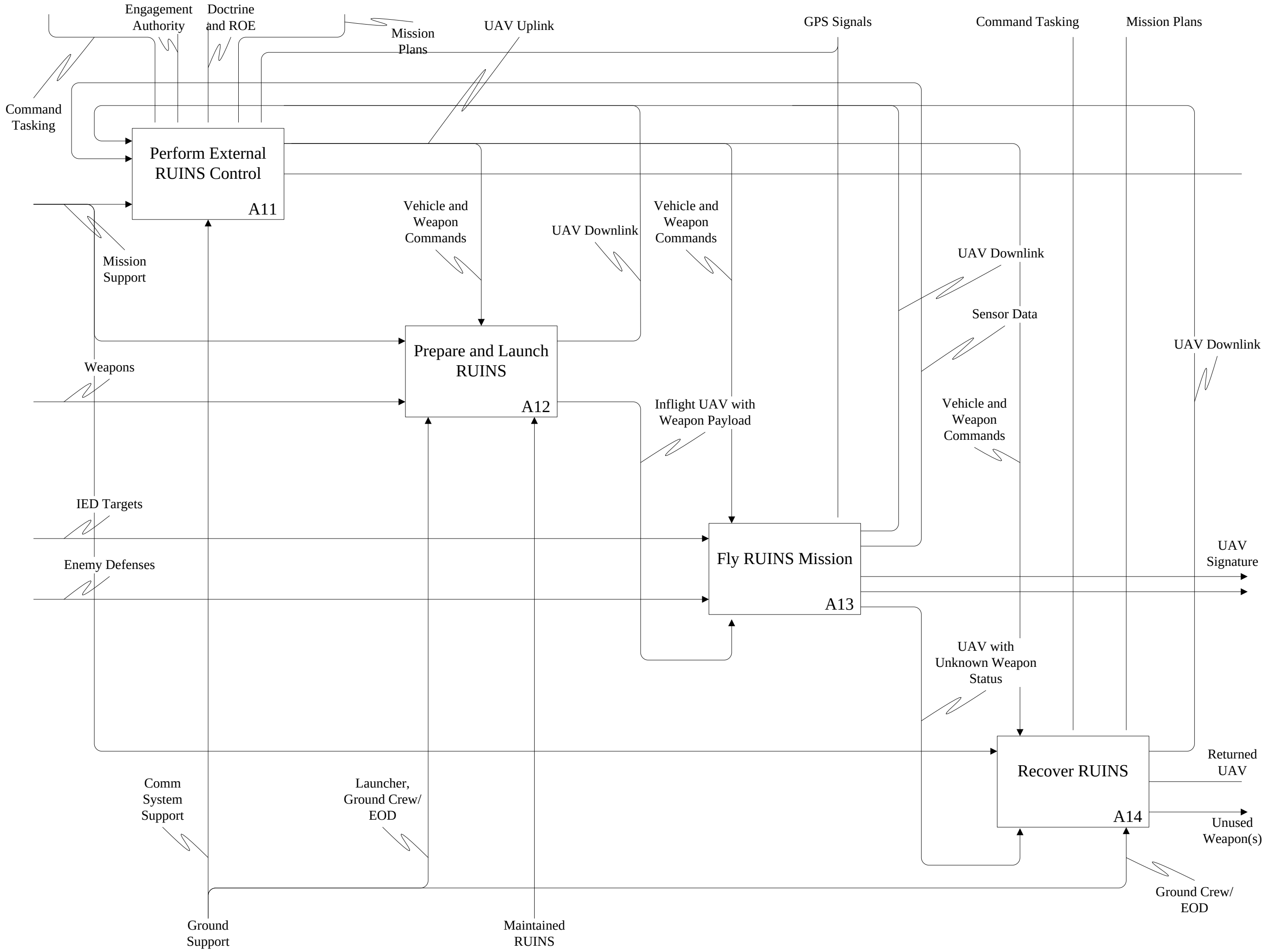


Figure C-3 - RUINS A0

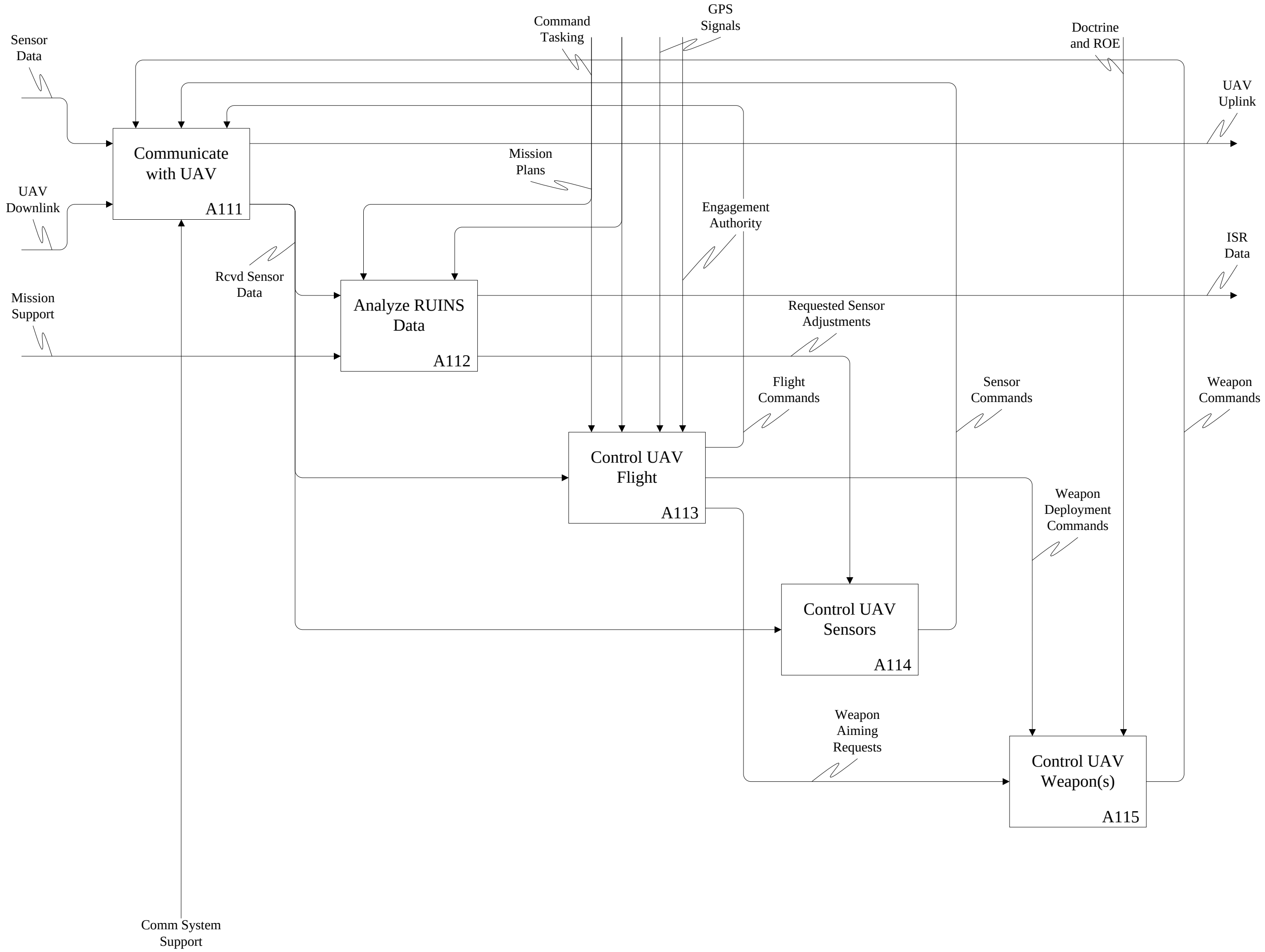


Figure C-4 - RUINS A1

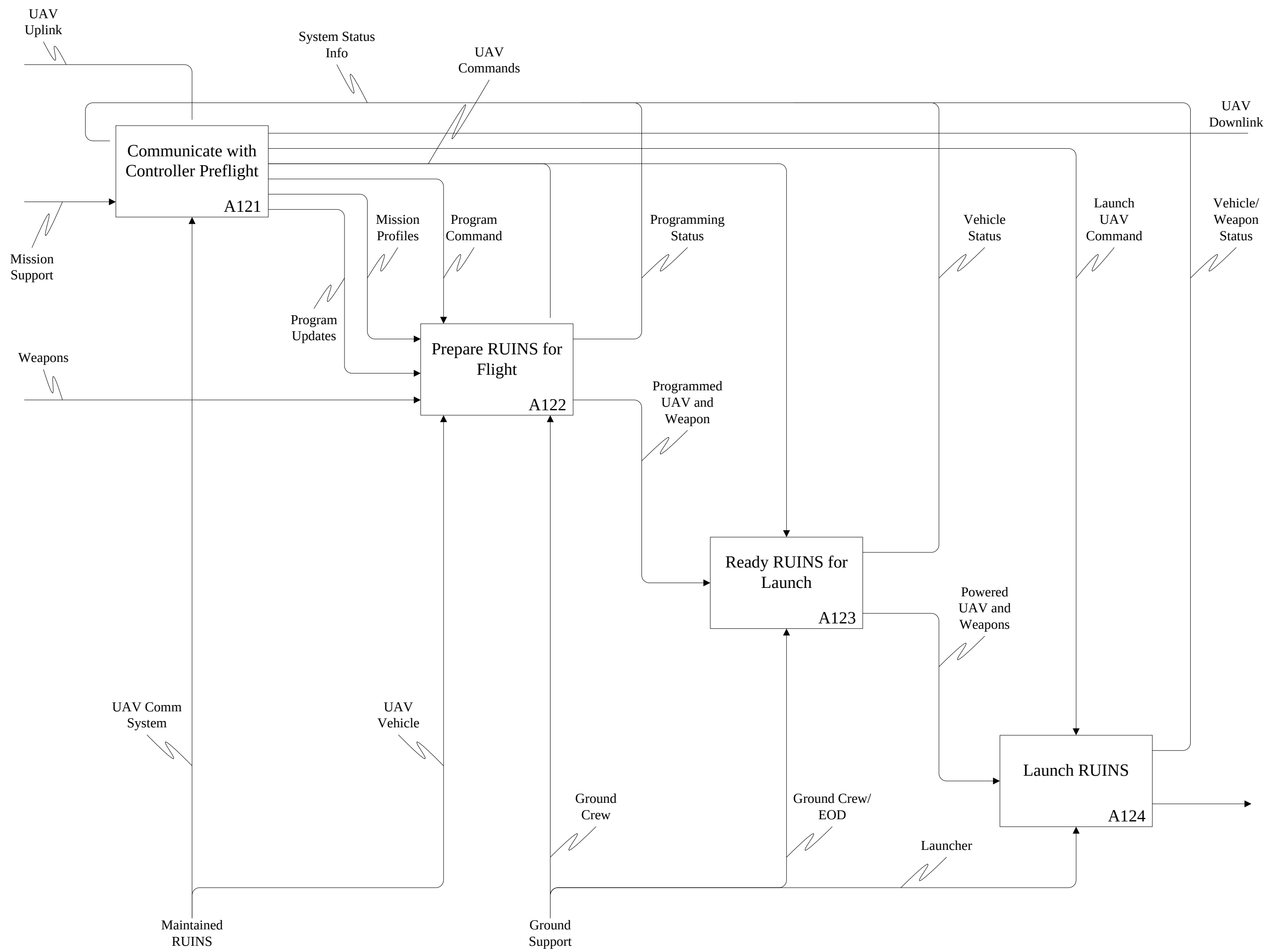


Figure C-5 - RUINS A2

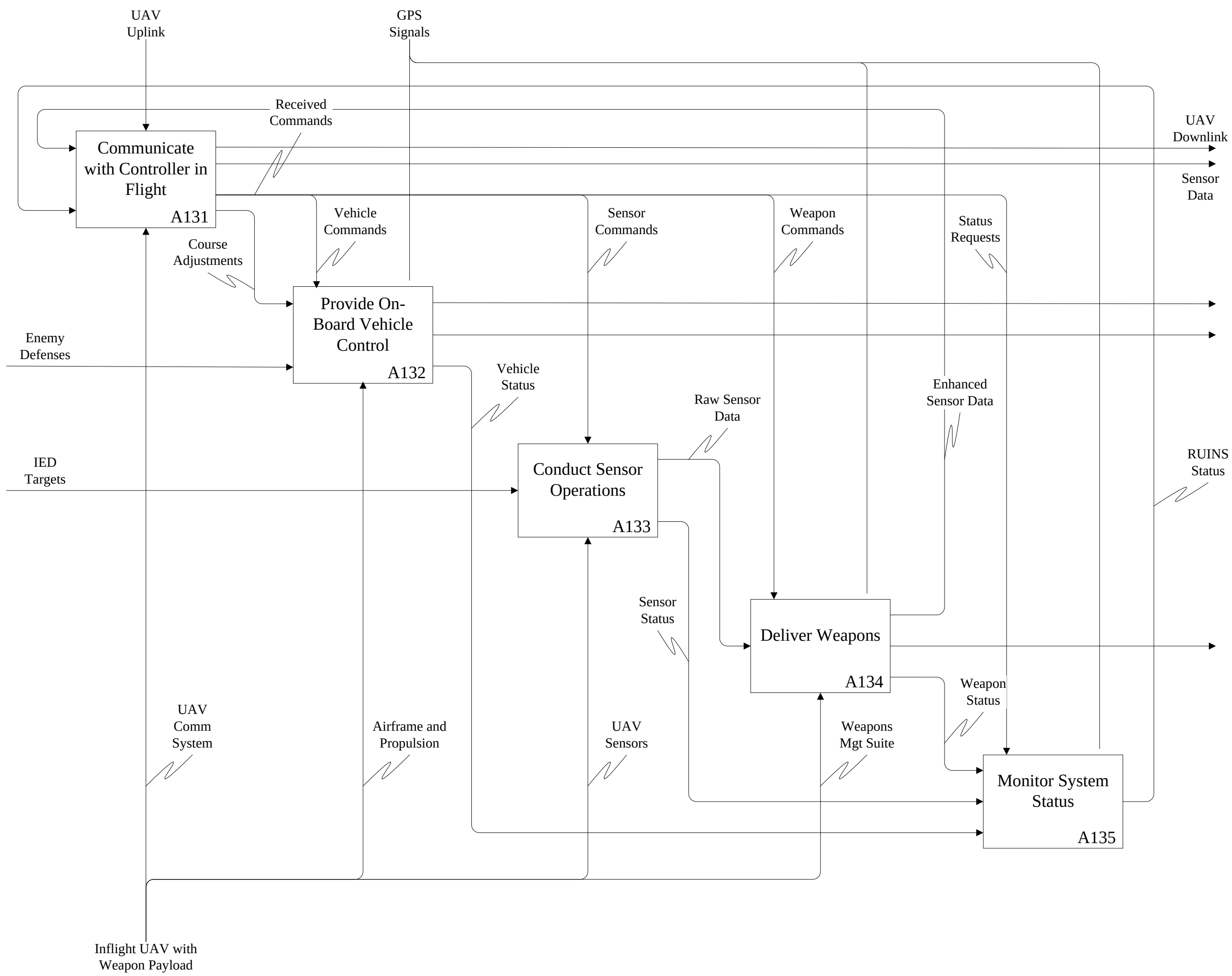


Figure C-6 - RUINS A3

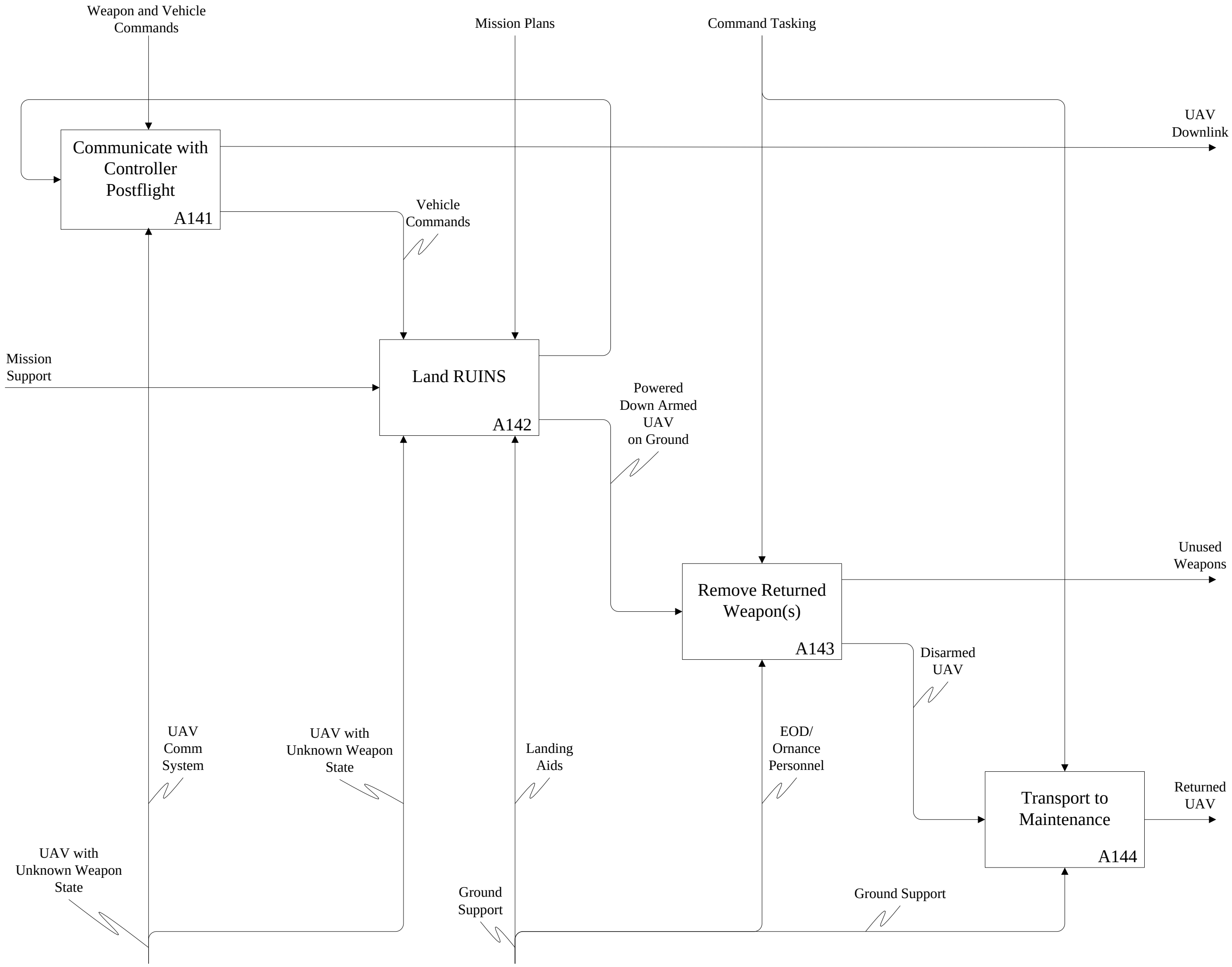


Figure C-7 - RUINS A4

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix D MODELING AND SUMULATION DATA

Table D-1 – RUINS Modeling & Simulation Results Summary - Bombs

Weapon	Altitude (ft)	Target Type	Time of Flight (s)	Miss Distance	Range (ft)	Detonation Result	Score
Bomb	2000	Fixed	23	687.47	2248.12	2	0
Bomb	500	Fixed	11	615.81	1275.94	2	0
Bomb	2000	Moving	23	734.04	2740.32	2	0
Bomb	500	Moving	10	665.48	1210.03	2	0
GB1	2000	Fixed	16	0.24	2248.12	1	1
GB1	500	Fixed	13	0.37	1215.20	1	1
GB1	2000	Moving	22	0.44	3159.52	1	1
GB1	500	Moving	12	0.43	2430.40	1	1
GB2	2000	Fixed	17	0.30	3281.04	1	1
GB2	500	Fixed	11	0.38	2248.12	1	1
GB2	2000	Moving	26	0.71	4253.20	1	1
GB2	500	Moving	13	0.40	2248.12	1	1

Table D-2 – RUINS Modeling & Simulation Results Summary - Missiles

Weapon	Altitude (ft)	Target Type	Time of Flight (s)	Miss Distance	Range (ft)	Detonation Result	Score
M1	2000	Fixed	16	81.51	2977.29	2	0
M1	500	Fixed	12	78.32	2308.92	2	0
M1	2000	Moving	16	394.46	3584.90	2	0
M1	500	Moving	13	154.46	3098.82	2	0
M2	2000	Fixed	28	0.42	5893.83	1	1
M2	500	Fixed	12	0.15	1397.51	1	1
M2	2000	Moving	22	16.92	3949.47	2	1
M2	500	Moving	15	39.62	2491.21	2	0
M3	2000	Fixed	23	1.98	4496.32	2	1
M3	500	Fixed	24	32.25	5590.02	2	1
M3	2000	Moving	18	4.20	3767.19	2	1
M3	500	Moving	26	43.20	7291.33	2	0
M4	2000	Fixed	51	0.69	10511.68	1	1
M4	500	Fixed	68	0.66	10511.68	1	1
M4	2000	Moving	56	0.25	12942.11	1	1
M4	500	Moving	85	0.16	15190.28	1	1
M5	2000	Fixed	10	117.05	7230.57	2	0
M5	500	Fixed	7	33.43	4739.37	2	0
M5	2000	Moving	11	192.96	7291.33	2	0
M5	500	Moving	8	64.88	6015.35	2	0

List of References

AAI Corporation. *AAI TEXTRON Systems: Shadow Tactical Unmanned Aircraft Systems.* 2010. http://www.aaicorp.com/products/uas/shadow_family.html (accessed December 28, 2010).

AeroVironment, Inc. *AeroVironment: Small UAS.* 2010. http://www.avinc.com/uas/ (accessed December 28, 2010).

—. *UAS Advanced Development:.* 2011. http://www.avinc.com/uas/adc/switchblade/ (accessed Jan 28, 2011).

AFDD 2.19. *Targeting.* HQ Air Force Doctrine Center/DR, 2006.

Alan Hobbs, Ph.D. and Stanley R. Herwitz, Ph.D. "Nasa." *Nasa website.* May 2006. http://human-factors.arc.nasa.gov/publications/UAV_interimreport_Hobbs_Herwitz.pdf.

Anderson, John D. *Introduction to Flight.* New York: McGraw-Hill, 2011.

Beach, Dr. Jefferey. *Naval Postgraduate School.* http://www.nps.edu/Academics/Institutes/Meyer/docs/Cost%20Engineering%201.pdf (accessed February 15, 2011).

Blanchard, Benjamin S., and Wolter J. Fabrycky. *Systems Engineering and Analysis.* 4th Edition. Upper Saddle River: Pearson Prentice Hall, 2006.

Boileau, Almerian R. "Atmospheric Properties." *Applied Optics, Vol. 3, No. 5,* 1964: 570-581.

Bone, Elizabeth, and Christopher Bolkcom. "Unmanned Aerial Vehicles:Background and issues for Congress." *www.fas.org/irp/crs/RL31872.pdf.* April 25, 2003. (accessed 2010).

Buede, Dennis M. *The Engineering Design of Systems: Models and Methods.* Hoboken: John Wiley and Sons, 2009.

Burke, Pete. "Precision Guided Mortar Munition." *DTIC.mil.* June 16, 2004. http://www.dtic.mil/ndia/2004armaments/DayII/SessionII/02Burke_PGMM.pdf (accessed Jan 24, 2011).

Chan, Apple. *The Human Ear.* August 2008. http://personal.cityu.edu.hk/~bsapplec/thehuman.htm (accessed November 14, 2010).

City Mayors. *The largest cities in the world by land area, population and density.* Jan 6, 2007. http://www.citymayors.com/statistics/largest-cities-density-125.html (accessed Feb 21, 2011).

DAU. *Defense Acquisition Guidebook.* Defense Acquisition University, 2010.

Defense Industry Daily. "Spike Missiles for Spain." *Defense Industry Daily.* Jan 28, 2008. http://www.defenseindustrydaily.com/spike-missiles-for-spain-04420/ (accessed Jan 24, 2011).

Defense Update. *ATK Offers Miniature Precision Guided Weapon for Unmanned Aerial Systems.* 2011. http://defense-update.com/products/m/31122010_miniature_munition_atk.html (accessed January 24, 2011).

—. "Lightweight Weapons for Autonomous Platforms." *Defense Update.* 2004-2009. http://defense-update.com/features/du-1-07/armedUAVs_5.htm (accessed Jan 24, 2011).

Department of the Army. *Improvised Explosive Device Defeat.* Washington, DC: Department of the Army, 2005.

DoD. *FY 2009-2034 Unmanned System Integrated Roadmap.* 2009. http://www.acq.osd.mil/psa/docs/UMSIntegratedRoadmap2009.pdf (accessed August 22, 2010).

Driels, Morris. *Weaponeering: Conventional Weapon System Effectiveness.* Reston, VA.: American Institute of Aeronautics and Astronautics, Inc., 2004.

DTIC. *SBIR N02-096: Very Low Noise, High Efficiency Propeller Designs for Small UAVs.* November 20, 2001. http://www.dtic.mil/dticasd/sbir/sbir021/sbir217.html (accessed December 20, 2010).

Dugas, D. J. *The Probability of Visual Detection of Reconnaissance Aircraft by Ground Observers.* Memorandum RM-4562-PR, Santa Monica: Rand Corporation, 1965.

Enemy Forces. *Assault Riffle AK-47.* 2010. http://www.enemyforces.net/firearms/ak47.htm (accessed January 31, 2011).

EuroSpike GmbH. "SPIKE-MR-LR.pdf." *Eurospike.com.* Unknown. http://www.eurospike.com/img/downloads/SPIKE-MR-LR.pdf (accessed Jan 24, 2011).

Fed Biz Ops. *Solicitation Number: FA8520-08-R-25412.* July 15, 2009. https://www.fbo.gov/index?s=opportunity&mode=form&id=3242013db05cc8ad874984d72bb174b1&tab=core&_cview=1 (accessed January 24, 2011).

—. *Solicitation Number: W31P4Q-10-R-0142.* April 19, 2010. https://www.fbo.gov/index?s=opportunity&mode=form&id=c31bcaaeabb86e6b9a29f250aaed2973&tab=core&_cview=0 (accessed November 24, 2010).

Federation of American Scientists. *Damage Criteria for Fragmentation Warheads.* Jan 20, 1998. http://www.fas.org/man/dod-101/navy/docs/es310/dam_crit/dam_crit.htm (accessed Jan 30, 2011).

—. *MK82 - Dumb Bombs.* April 23, 2000. http://www.fas.org/man/dod-101/sys/dumb/mk82.htm (accessed February 2011).

—. *MK84 - Dumb Bombs.* April 23, 2000. http://www.fas.org/man/dod-101/sys/dumb/mk84.htm (accessed February 2011).

Felix, Steve. "U.S. Navy Spike Missile System: A New Generation of Miniature Precision Guided Weapons." *DTIC.mil.* May 1, 2006.

http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA500538 (accessed Jan 24, 2011).

Flightglobal. *Flightglobal: Navmar - Tiger Shark LR3*. 2010. http://www.flightglobal.com/directory/detail.aspx?aircraftCategory=UAV&manufacturerType=UAV&navigationItemId=374&aircraftId=3532&manufacturer=21986&keyword=&searchMode=Keyword&units=Imperial (accessed December 28, 2010).

GAO. "Government Accountability Office." *Government Accountability Office.* December 19, 2005. www.gao.gov/ (accessed October 31, 2010).

—. "Government Accountability Office." *Government Accountability Office.* July 2009. www.gao.gov/ (accessed November 2010).

Global Security. August 1999. http://www.globalsecurity.org/military/library/policy/navy/ntsp/UAV.htm (accessed August 08, 2010).

Gormley, Dennis, and Richard Speier. "Controlling Unmanned Air Vehicles: New Challenges." Non-Proliferation Education Center, March 19, 2003.

Grabowsky, John. "Future Solutions - ISR." *DTIC.gov.* Apr 2007. http://www.dtic.mil/ndia/2007pto/Wednesday/mrJohnGrabowsky.pdf (accessed Jan 28, 2011).

Green, John. "Modeling the Ship as a Weapon System." *Presentation, AIAA 2nd Biennial National Forum on Weapon System Effectiveness*. Washington DC, March 27-29, 2001.

Grime. "Javelin Model." *Grime.net.* 2007. http://www.grime.net/facets/models/javelin.htm (accessed Jan 25, 2011).

Harris, Tom. *How Hearing Works.* 2011. http://health.howstuffworks.com/human-body/systems/ear/hearing.htm (accessed 1 16, 2011).

Haskins, Cecilia. *SYSTEMS ENGINEERING HANDBOOK.* Seattle: International Council on Systems Engineering (INCOSE), 2007.

IHS Global Limited. "AAI Shadow 400 and 600." *Jane's Unmanned Aerial Vehicles and Targets.* September 28, 2010. http://search.janes.com.libproxy.nps.edu/Search/documentView.do?docId=/content1/janesdata/binder/juav/juav0735.htm@current&pageSelected=allJanes&keyword=shadow%20600&backPath=http://search.janes (accessed January 28, 2011).

—. "FIM-92 Stinger (Air-To-Air Stinger, ATAS)." *Jane's Defense Equipment and Technology.* Dec 3, 2010. http://jdet.janes.com/JDIC/JDET/documentView.do?docId=/content1/janesdata/binder/jalw/jalw3616.htm@current&pageSelected=&keyword=stinger&backPath=http://jdet.janes.com/JDIC/JDET&Prod_Name=JALW&activeNav=/JDIC/JDET#img (accessed Jan 24, 2011).

—. "GBU-31, GBU-32 and GBU-38 Joint Direct Attack Munition (JDAM) ." *IHS Jane's: Defence & Security Intelligence & Analysis.* January 20, 2010. http://search.janes.com.libproxy.nps.edu/Search/documentView.do?docId=/content1/janesdata/binder/jalw/jalw3667.htm@current&pageSelected=allJanes&keyword=JDAM&backPath=http://search.janes.com/Search&Prod_Name=JALW& (accessed February 10, 2011).

—. "Jane's Air-Launched Weapons: CBU-97/B and CBU-105/B Sensor Fuzed Weapon (SFW), STS." *IHS Jane's: Defence & Security Intelligence & Analysis.* January 22, 2010. http://search.janes.com.libproxy.nps.edu/Search/documentView.do?docId=/content1/janesdata/binder/jalw/jalw3663.htm@current&pageSelected=allJanes&keyword=selectively targeted skeet&backPath=http://search.janes.com/Search&Prod_Name=JALW& (accessed February 2011).

—. "Jane's Land-Based Air Defence: FIM-92 Stinger." *IHS Jane's: Defence & Security Intelligence & Analysis.* August 04, 2010. http://search.janes.com.libproxy.nps.edu/Search/documentView.do?docId=/content1/jane

sdata/yb/jlad/jlad0030.htm@current&pageSelected=allJanes&keyword=fim-92%20stinger%20cost&backPath=http://search.janes.com/Search&Prod_Name=JLAD& (accessed February 2011).

—. "Javelin advanced medium anti-tank weapon system." *Jane's Defence Equipment and Technology* . Nov 9, 2010. http://jdet.janes.com/JDIC/JDET/documentView.do?docId=/content1/janesdata/yb/jiw/jiw_0808.htm@current&pageSelected=&keyword=javelin_anti-tank&backPath=http://jdet.janes.com/JDIC/JDET&Prod_Name=JIW&activeNav=/JDIC/JDET (accessed Jan 24, 2011).

—. "Javelin advanced medium anti-tank weapon system." *IHS Jane's: Defence & Security Intelligence & Analysis.* November 09, 2010. http://search.janes.com.libproxy.nps.edu/Search/documentView.do?docId=/content1/janesdata/yb/jiw/jiw_0808.htm@current&pageSelected=allJanes&keyword=javelin&backPath=http://search.janes.com/Search&Prod_Name=JIW& (accessed February 2011).

—. "Spike multi-purpose precision weapon systems." *Jane's Defence Equipment and Technology* . Dec 6, 2010. http://jdet.janes.com/JDIC/JDET/documentView.do?docId=/content1/janesdata/yb/jiw/jiw_0758.htm@current&pageSelected=&keyword=javelin&backPath=http://jdet.janes.com/JDIC/JDET&Prod_Name=JIW&activeNav=/JDIC/JDET (accessed Jan 24, 2011).

Israel Aerospace Industries. *POP300D.* 2009. http://www.iai.co.il/sip_storage/files/0/36970.pdf (accessed 01 18, 2011).

Jackson Hole Scientific Investigations . *Supplemental Vehicle Sound Measurements.* Febuary 6, 2002. http://wyotrails.state.wy.us/Research/SoundLevel.asp (accessed 2 4, 2011).

Jane's Defense Equipment and Technology. *AK-47 7.62mm assault rifle.* July 5, 2010. http://jdet.janes.com/JDIC/JDET/documentView.do?docId=/content1/janesdata/yb/jiw/ji

w_0423.htm@current&pageSelected=&keyword=&backPath=http://jdet.janes.com/JDIC/JDET&Prod_Name=JIW&activeNav=/JDIC/JDET (accessed January 05, 2011).

JIEDDO. *Joint Improvised Explosive Device Defeat Organization.* August 2010. https://www.jieddo.dod.mil/content/docs/20100804_JIEDDO_Fact_Sheet.pdf (accessed August 28, 2010).

Johnson, John. "Analysis of Image Forming Systems." *Image Intensifier Symposium.* Fort Belvoir, 1958. 249-273.

Koopman, Bernard Osgood. *OEG Report 56: Search and Screening.* DoD, Washington D.C.: Office of Chief of Naval Operations, 1946.

Kopeika, Norman S. *A Systems Engineering Approach to Imaging.* Bellingham: The Society of Photo-Optical Instrumentation Engineers, 1998.

L3 Communications. *L3 Unmanned Systems: Cutlass Tube-Launched Small UAS.* July 15, 2009. http://www.genaero.com/pdf_uas/tech/Cutlass.pdf (accessed December 28, 2010).

Lockheed-Martin. *Hellfire M299 Missile Launcher.* 2011. http://www.lockheedmartin.com/data/assets/mfc/PC/M299_ProductCard.pdf (accessed January 24, 2011).

Marte, Jack E., and Donald W. Kurtz. *A Review of Aerodynamic Noise from Propellers, Rotors, and Lift Fans.* Technical, Pasadena: NASA, 1970.

Mathews, Staci. "NAWCWD Corporate Communications: News Release." *Weapons Division PAO.* February 20, 2008. http://www.navair.navy.mil/nawcwd/nawcwd/news/2008/2008-02_spike_demo.htm (accessed February 2011).

Miller, C. J. *Noise Analysis of UAV Propeller.* November 15, 2001. http://www.dtic.mil/dticasd/sbir/sbir021/n096.pdf (accessed October 25, 2010).

Naval Center for Cost Analysis. *NCCA Inflation Indices.* January 2010. http://www.ncca.navy.mil/services/inflation.cfm (accessed February 2011).

Net Resources International. "Javelin Anti-Armour Missile." *Army-Technology.com.* 2011. http://www.army-technology.com/projects/javelin/ (accessed Jan 24, 2011).

Oates, Lieutant General Michael. "Joint IED Defeat Organization." *Joint IED Defeat Organization web site.* August 22, 2010. http://www.ngaus.org/ngaus/files/ccLibraryFiles/Filename/000000006898/oates.pdf.

O'Connor, Phillip. "Fort Leonard Wood Center Fights IED Threat." *stltoday.com.* July 11, 2010. http://www.stltoday.com/news/local/metro/article_cb99f1b9-0cec-5c02-a555-407b3cf4d08d.html (accessed August 25, 2010).

Office of Management and Budget. *Circular A-94 Appendix C | The White House.* December 2010. http://www.whitehouse.gov/omb/circulars_a094_a94_appx-c/ (accessed February 2011).

Office of the Secretary of Defense. "Federation of American Scientists." *Federation of American Scientists.* August 2005. www.fas.org/irp/program/collect/uav_roadmap2005.pdf (accessed October 31, 2010).

Operations Evaluation Group. *Visual Detection in Air Interception: A Comparison of Theory with Trial Results.* DoD Report, Alexandria: Defense Documentation Center for Scientific and Technical Information, 1952.

Pakistan Defence. Nov 17, 2008. http://www.defence.pk/forums/land-forces/16366-army-air-defence-firing-exercise-sonmiani.html (accessed Jan 05, 2011).

Pakistan Defence. Sept 24, 2009. http://www.defence.pk/forums/india-defence/34860-indian-army-small-arms-thread-2.html (accessed Jan 5, 2011).

Parsch, Andreas. *Directory of U.S. Military Rockets and Missiles Appendix 2: Modern UAVs RQ-2.* July 25, 2007. http://www.designation-systems.net/dusrm/app2/q-2.html (accessed December 28, 2010).

Raytheon. "Stinger Information." *Raytheon.com.* http://www.raytheon.com/capabilities/products/stellent/groups/public/documents/content/cms01_057590.pdf (accessed Jan 24, 2011).

Royal Mechanical. 5 8, 2010. http://www.roymech.co.uk/Useful_Tables/Human/Human_sizes.html (accessed 2 12, 2011).

SA-7 GRAIL. March 29, 1999. http://www.fas.org/man/dod-101/sys/missile/row/sa-7.htm (accessed January 5, 2011).

Savio D Silva Network. *Diagram of the Eye - Human Eye Diagrams.* 2010. http://www.osovo.com/diagram/eyediagram.htm (accessed October 28, 2010).

Schaffer, M.B. *Basic Measures for Comparing the Effectiveness of Conventional Weapons.* Memorandum RM-4647-PR, Santa Monica: RAND Corporation, 1966.

Selinger, Marc. "Navy Plans to Adapt Spike Missile to Unmanned Vehicles." *Aviation Week's Aerospace Daily*, 2003: 1.

Silex Innovations. *Sound Attenuation.* April 5, 2002. http://www.silex.com/pdfs/Sound%20Attenuation.pdf (accessed October 25, 2010).

Simpson, Jason. "JIEDDO to Field USAF-Specific Counter-IED Unmanned Aircraft This Year." January 29, 2009. http://integrator.hanscom.af.mil/2009/January/01292009/01292009.htm.

Strategy Page. *Expendable Switchblade.* May 21, 2010. http://www.strategypage.com/htmw/htairw/20100521.aspx (accessed Jan 28, 2011).

Strategy World. *Air Weapons: Expendable Switchblade.* May 21, 2010. https://www.strategyworld.com/htmw/htairw/20100521.aspx (accessed February 2011).

Taylor, John H. "Use of Visual Performance Data In Visibility Prediction." *Applied Optics, Vol. 3, No. 5*, 1964: 562-569.

Textron Systems. *Selectively Targeted Skeet™ (STS) Submunition.* 2011. http://www.textrondefense.com/products/airlaunched/sts.htm (accessed January 24, 2011).

Thales. *Tactical UAV Systems.* http://www.thalesgroup.com/Portfolio/Defence/Aerospace_Product_TacticalUAV/?pid=1568 (accessed October 3, 2010).

Theiss Aviation. *Theiss Aviation: Tarzan TD-1C.* July 8, 2010. http://www.theissaviation.com/tarzan.html (accessed 28 2010, December).

U.S. Army. "Federation of American Scientists." June 1995. http://www.fas.org/irp/doddir/army/fm34-25-2/index.html.

U.S. Army. "FM 3-21.75." *The Warrior Ethos and Soldier Combat Skills*, January 2008.

U.S. Army Training and Doctrine Command. *TRADOC BULLETIN 3. SOVIET RPG-7 ANTITANK GRENADE LAUNCHER.* Training Bulletin, Fort Monroe: HQ U.S. ARMY TRAINING AND DOCTRINE COMMAND, 1976.

U.S. Army UAS Center of Excellence. ""Eyes of the Army" U.S Army Roadmap for Unmanned Aircraft Systems 2010-2035." April 2010. http://www.fas.org/irp/program/collect/uas-army.pdf (accessed August 20, 2010).

USMC. "Improvised Explosive Device Defeat." *FMI 3-34.119/MCIP 3-17.01*, September 2005.

Wikipedia. *Wikipedia: DRS Sentry HP*. November 23, 2010. http://en.wikipedia.org/wiki/DRS_Sentry_HP (accessed December 28, 2010).

Wilson, Clay. *Improvised Explosive Devices (IEDs) in Iraq: Effects and Countermeasures.* February 10, 2006. http://www.history.navy.mil/library/online/ied.htm#fn3 (accessed July 17, 2010).

THIS PAGE INTENTIONALLY LEFT BLANK

Initial Distribution List

1. Defense Technical Information Center
8725 John J. Kingman Rd., STE 0944
Ft. Belvoir, VA 22060-6218

2. Dudley Knox Library, Code 013
Naval Postgraduate School
Monterey, CA 93943-5100

3. Joseph W. Sweeney III
Naval Postgraduate School
Monterey, CA 93943-5100

3. Mark Rhoades
Naval Postgraduate School
Monterey, CA 93943-5100